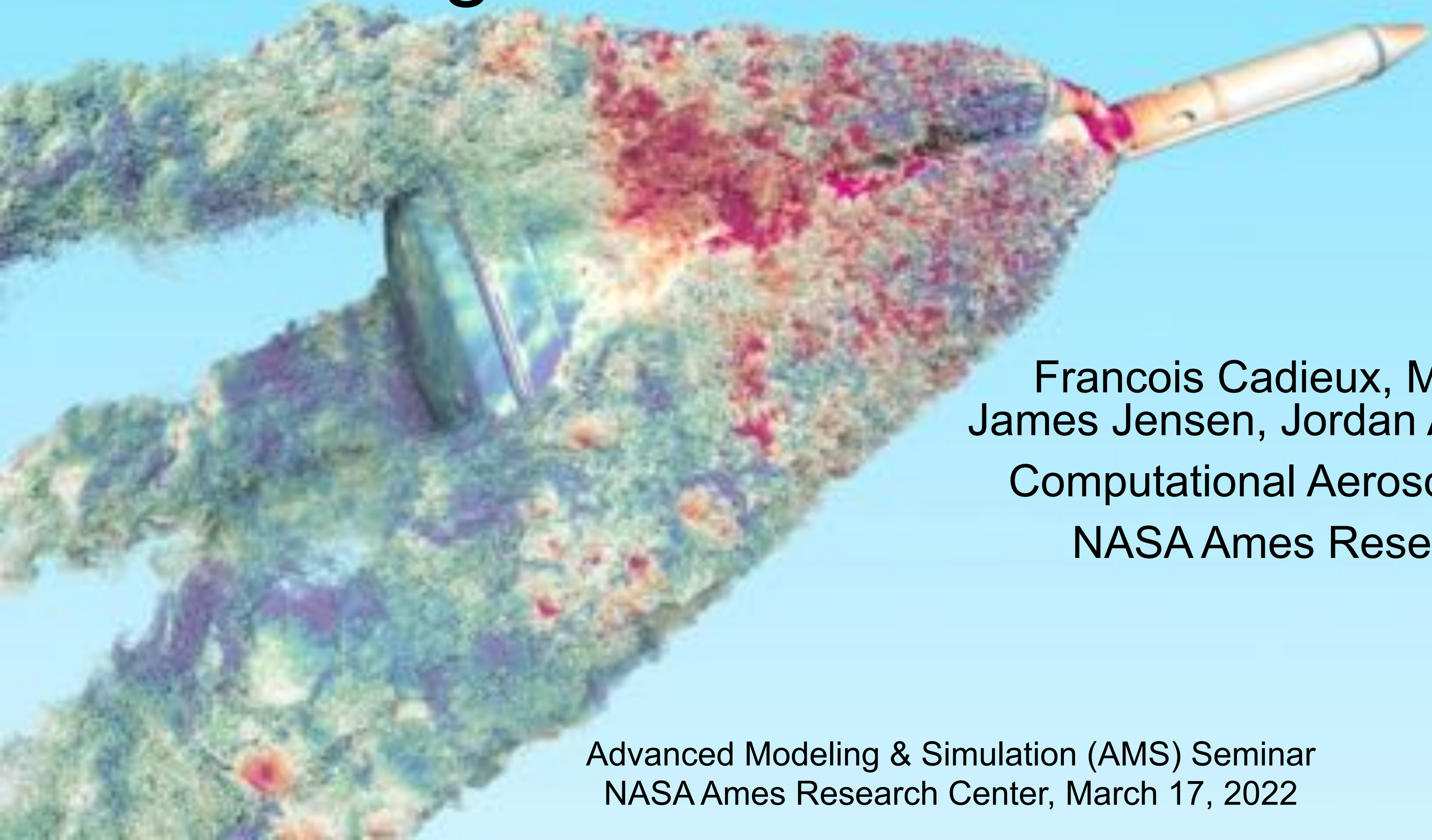
Predicting Orion Launch Abort Acoustics



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Computational Aerosciences Branch

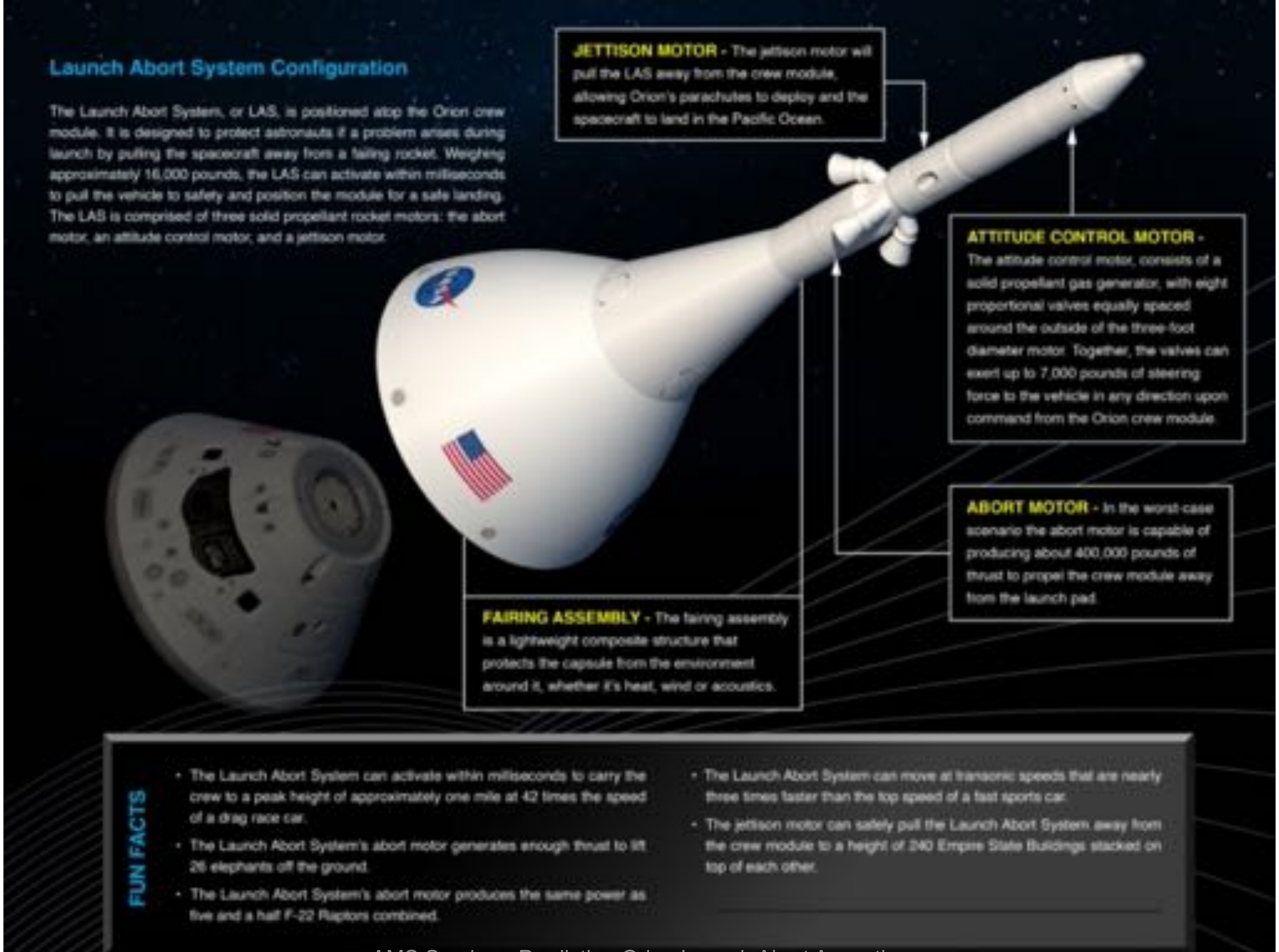
NASA Ames Research Center

Advanced Modeling & Simulation (AMS) Seminar
NASA Ames Research Center, March 17, 2022

Space Launch System (SLS)

Onward to the Moon and Mars


National Aeronautics and Space Administration
ORION
Launch Abort System (LAS)
NASAfacts
Ensuring Astronaut Safety
NASA is developing technologies that will enable humans to explore new destinations in the solar system. America will use the Orion spacecraft, launched atop the Space Launch System rocket, to send a new generation of astronauts beyond low-Earth orbit to places like an asteroid and eventually Mars. In order to keep astronauts safe in such difficult, yet exciting missions, NASA and Lockheed Martin collaborated to design and build the Launch Abort System.


Launch Abort System Configuration
The Launch Abort System, or LAS, is positioned atop the Orion crew module. It is designed to protect astronauts if a problem arises during launch by pulling the spacecraft away from a failing rocket. Weighing approximately 16,000 pounds, the LAS can activate within milliseconds to pull the vehicle to safety and position the module for a safe landing. The LAS is comprised of three solid propellant rocket motors: the abort motor, an attitude control motor, and a jettison motor.
JETTISON MOTOR - The jettison motor will pull the LAS away from the crew module, allowing Orion's parachutes to deploy and the spacecraft to land in the Pacific Ocean.
ATTITUDE CONTROL MOTOR - The attitude control motor, consists of a solid propellant gas generator, with eight proportional valves equally spaced around the outside of the three-foot diameter motor. Together, the valves can exert up to 7,000 pounds of steering force to the vehicle in any direction upon command from the Orion crew module.
ABORT MOTOR - In the worst-case scenario the abort motor is capable of producing about 400,000 pounds of thrust to propel the crew module away from the launch pad.
FAIRING ASSEMBLY - The fairing assembly is a lightweight composite structure that protects the capsule from the environment around it, whether it's heat, wind or acoustics.
FUN FACTS
• The Launch Abort System can activate within milliseconds to carry the crew to a peak height of approximately one mile at 42 times the speed of a drag race car.
• The Launch Abort System's abort motor generates enough thrust to lift 26 elephants off the ground.
• The Launch Abort System's abort motor produces the same power as five and a half F-22 Raptors combined.
• The Launch Abort System can move at transonic speeds that are nearly three times faster than the top speed of a fast sports car.
• The jettison motor can safely pull the Launch Abort System away from the crew module to a height of 240 Empire State Buildings stacked on top of each other.

Using HPC To Enhance Astronaut Safety

- Jan 2017: Start of a collaboration between Orion Loads and Dynamics team at Johnson Space Center and Launch, Ascent, and Vehicle Aerodynamics (LAVA) team at Ames

- Goal: Incorporate Computational Fluid Dynamics (CFD) predictions to the wind tunnel, ground, and flight test data used to characterize the vibro-acoustic environment of the Orion Launch Abort System (LAS) – to ensure it doesn't shake itself apart

- Motivation:
  - To help reduce uncertainty: WT/ground/flight tests are few in number, have limited sensors, are costly, and don't cover all possible abort trajectories
  - To help better understand how altitude, Mach number, and acceleration, affect the strength and distribution of vibrations on LAS

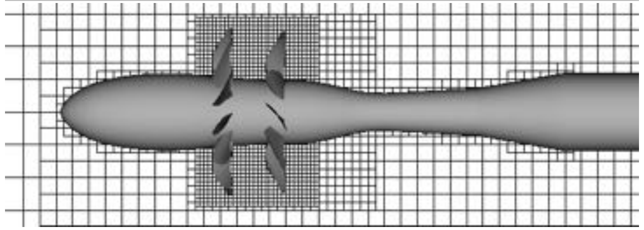
First Step is CFD Validation

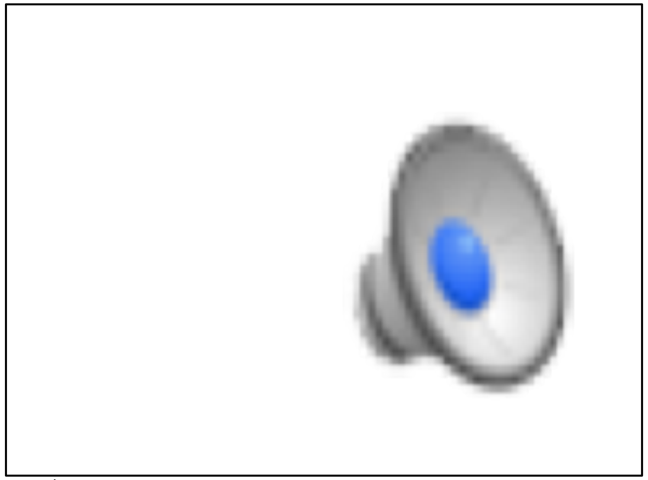
- Predict transient pressure loads and acoustics on near field plume acoustics towers, heat shield cage structure, and crane ahead of QM-1 abort motor ground test

Pictures from QM-1 abort motor ground test, June 15, 2017

CFD Grid Paradigms in LAVA

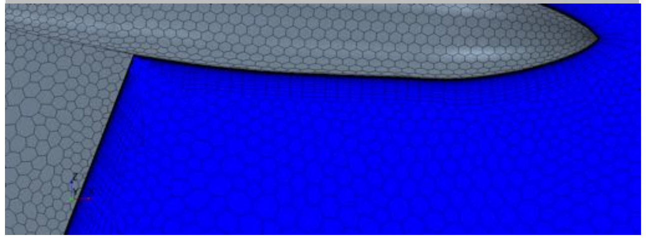
Structured Cartesian AMR

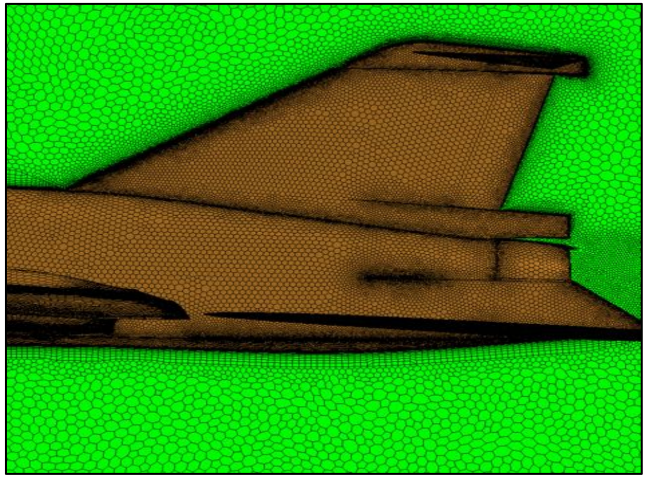




- ✓ Fully-automated grid generation
- ✓ Highly efficient Adaptive Mesh Refinement (AMR)
- ✓ Low computational cost
- ✓ Reliable higher order methods
- ✗ Non-body fitted → Resolution of boundary layers challenging

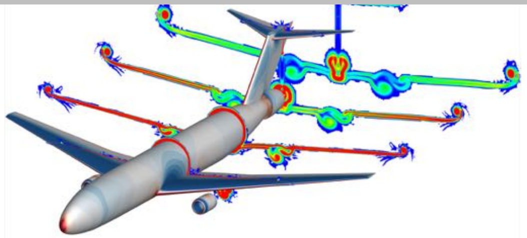
Unstructured Arbitrary Polyhedral

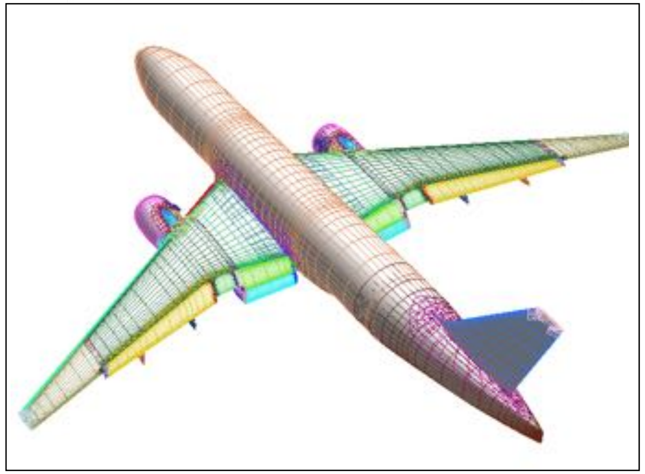




- ✓ Partially automated grid generation
- ✓ Body fitted grids
- ✗ Grid quality can be challenging
- ✗ High computational cost
- ✗ Higher order methods yet to fully mature

Structured Curvilinear

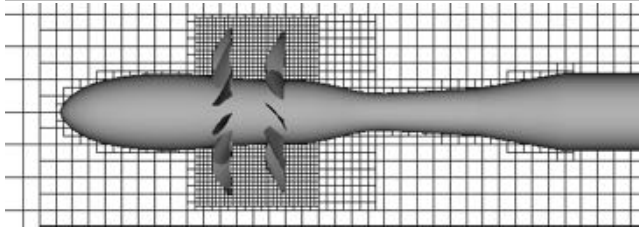


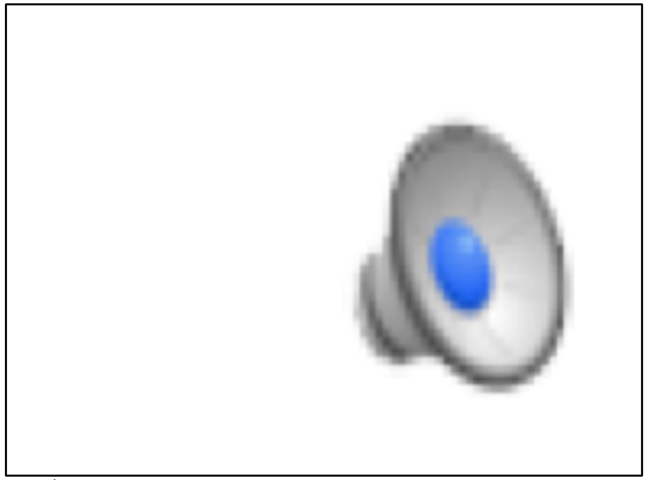


- ✓ High quality body fitted grids
- ✓ Low computational cost
- ✓ Reliable higher order methods
- ✗ Grid generation largely manual and time consuming

Initial CFD Goals

Structured Cartesian AMR





- ✓ Fully-automated grid generation
- ✓ Highly efficient Adaptive Mesh Refinement (AMR)
- ✓ Low computational cost
- ✓ Reliable higher order methods
- ✗ Non-body fitted → Resolution of boundary layers challenging

Predict transient pressure loads and acoustics on structures for QM-1 abort motor ground test:

- Simulate complex geometry over large domain
  - ✓ Automatic mesh generation and immersed boundary representation
- Track ignition overpressure (IOP) wave as it propagates
  - ✓ Solution-based adaptive mesh refinement (AMR)
- Capture high Mach number turbulent plume acoustics
  - ✓ Robust high-order scheme in space and time
  - ✓ Near-isotropic cells are best for predicting jet noise
  - ✓ **Boundary layers do not play a critical role for the quantities of interest for this project**
- Short turnaround time for decision making
  - ✓ Automatic grid generation means we can get started immediately
  - ✓ Block-structured framework increases computational efficiency

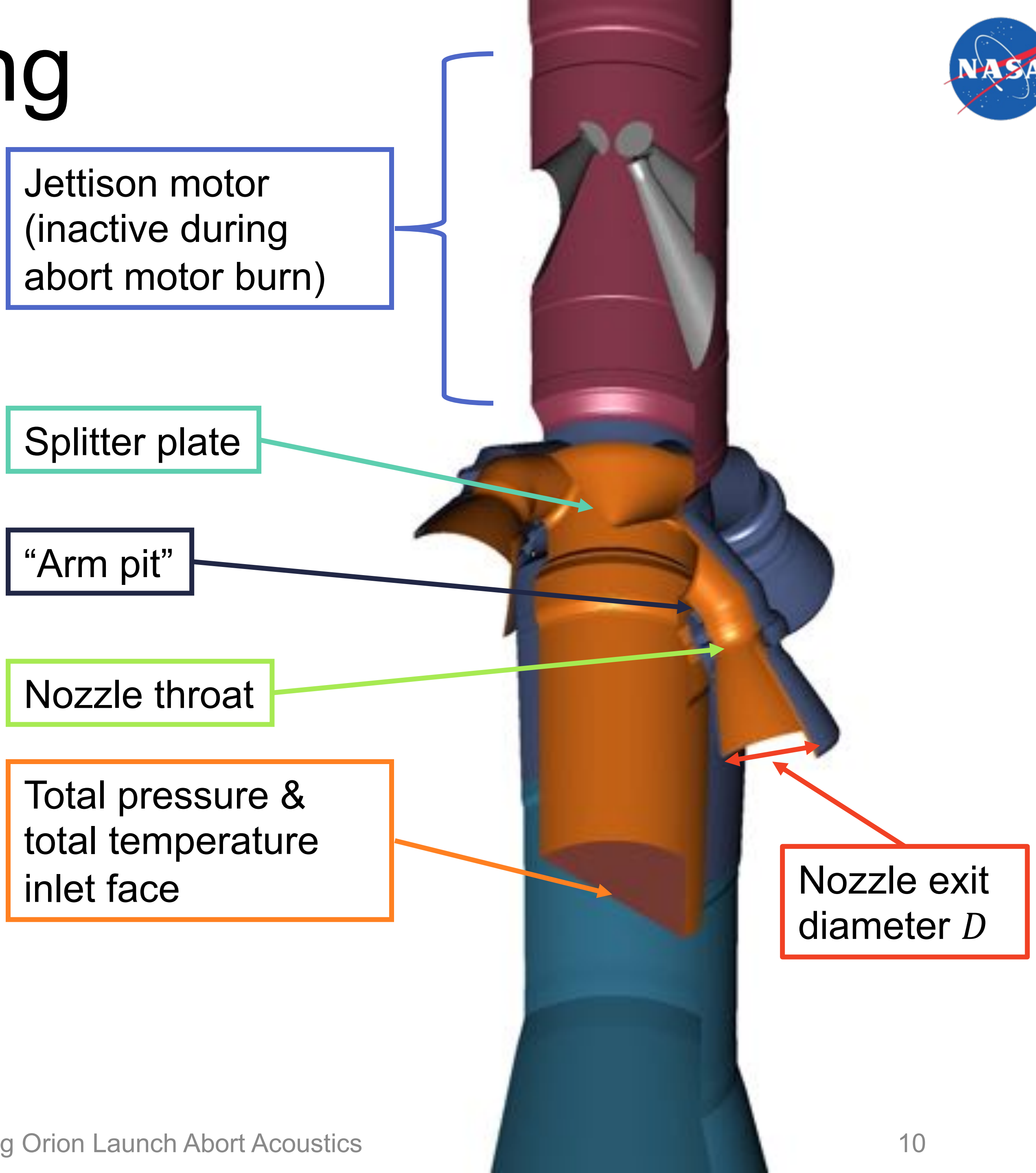
Numerical Methodology

- Solve compressible Navier-Stokes equations with 2 non-reacting species: air and exhaust gas
- Convective flux: 5th order weighted essentially non-oscillatory (WENO) conservative finite difference scheme with improved weights (Z-WENO5) in characteristic space with Rusanov flux-vector splitting [1]
- Flux limiter: blend high-order flux with local Lax-Friedrich's flux to ensure positivity of pressure and density only if necessary [2]
- Viscous flux: second order centered
- Turbulence model: N/A → implicit large-eddy simulation (ILES)
- Time integration: explicit 3rd or 4th order Runge-Kutta with CFL $\leq$ 1
- Wall treatment: slip adiabatic walls through 2nd order ghost cell method

[1] C. Brehm, M. Barad, J. Housman, and C. Kiris. A Comparison of Higher-Order Finite-Difference Shock Capturing Schemes. Computers & Fluids, 122:184-208, November 2015.
[2] Xiangyu Y Hu, Nikolaus A Adams, and Chi-Wang Shu. Positivity-preserving method for high-order conservative schemes solving compressible Euler equations. Journal of Computational Physics, 242:169-180, 2013.

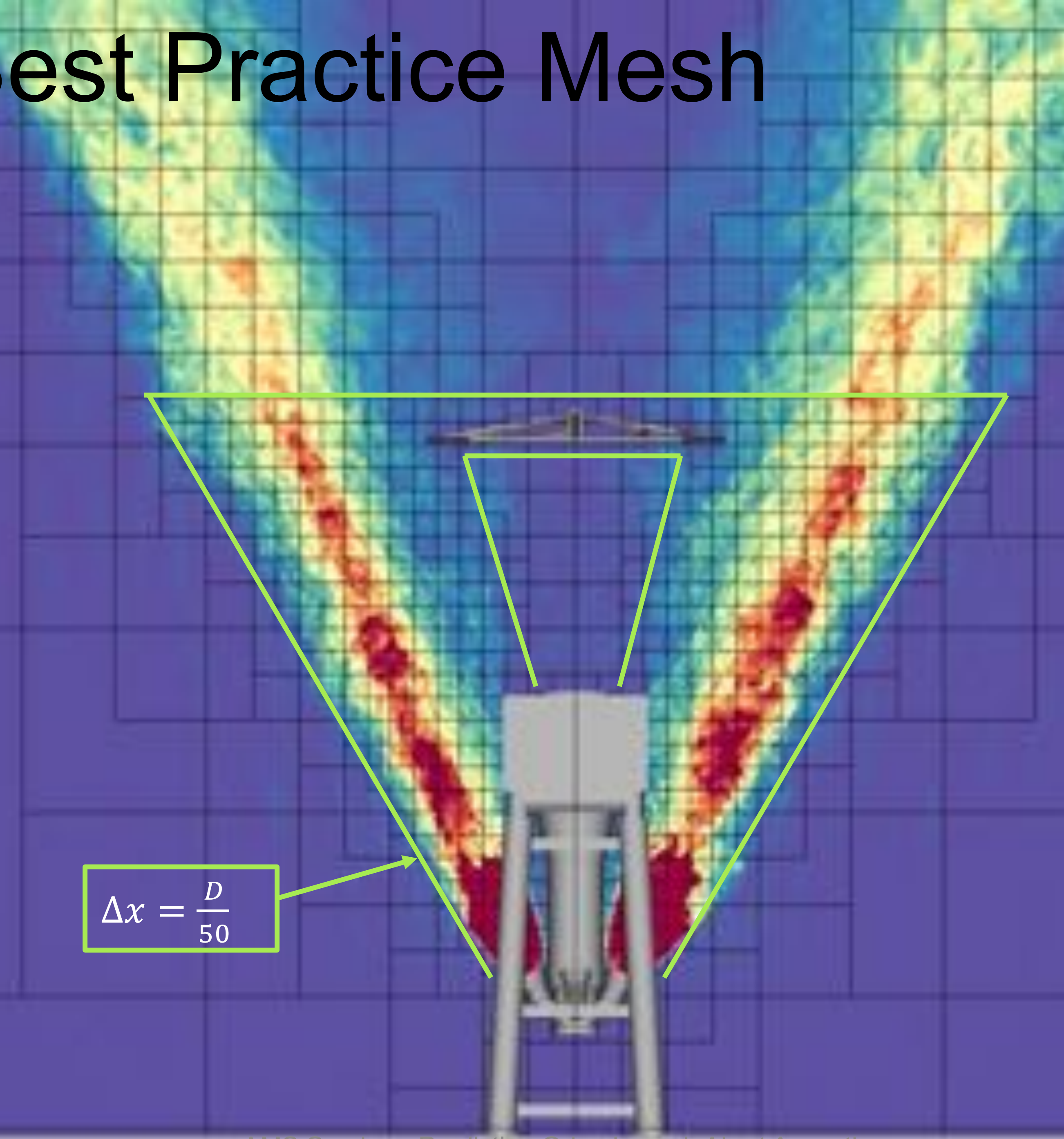
Abort Motor Modeling

- Due to abrupt flow turning abort motor design, nozzle exit flow is not axisymmetric about nozzle centerline, so need to start simulation upstream
- Use measured combustion chamber time varying-values as total pressure and temperature inlet condition at face inside grain silo, well upstream of nozzle splitter plate and throat
- Exhaust gas from solid rocket motor is treated as a non-reacting mixture of the combustion byproducts (Al_2O_3 powder, steam, H_2, HCl, CO, CO_2, etc.): combustion effects (afterburning, heat radiation, soot/particulate production, etc) are ignored to reduce computational cost



QM-1 Best Practice Mesh

Fixed user-defined refinement volumes. 600M cells overall, 60% of which are on finest refinement level. Fine mesh tracks plumes and connects noise source to heat shield sensor structure.



Each box contains 32^3 cells. Mach number shows the location of the plumes.

QM-1 CFD Visualization

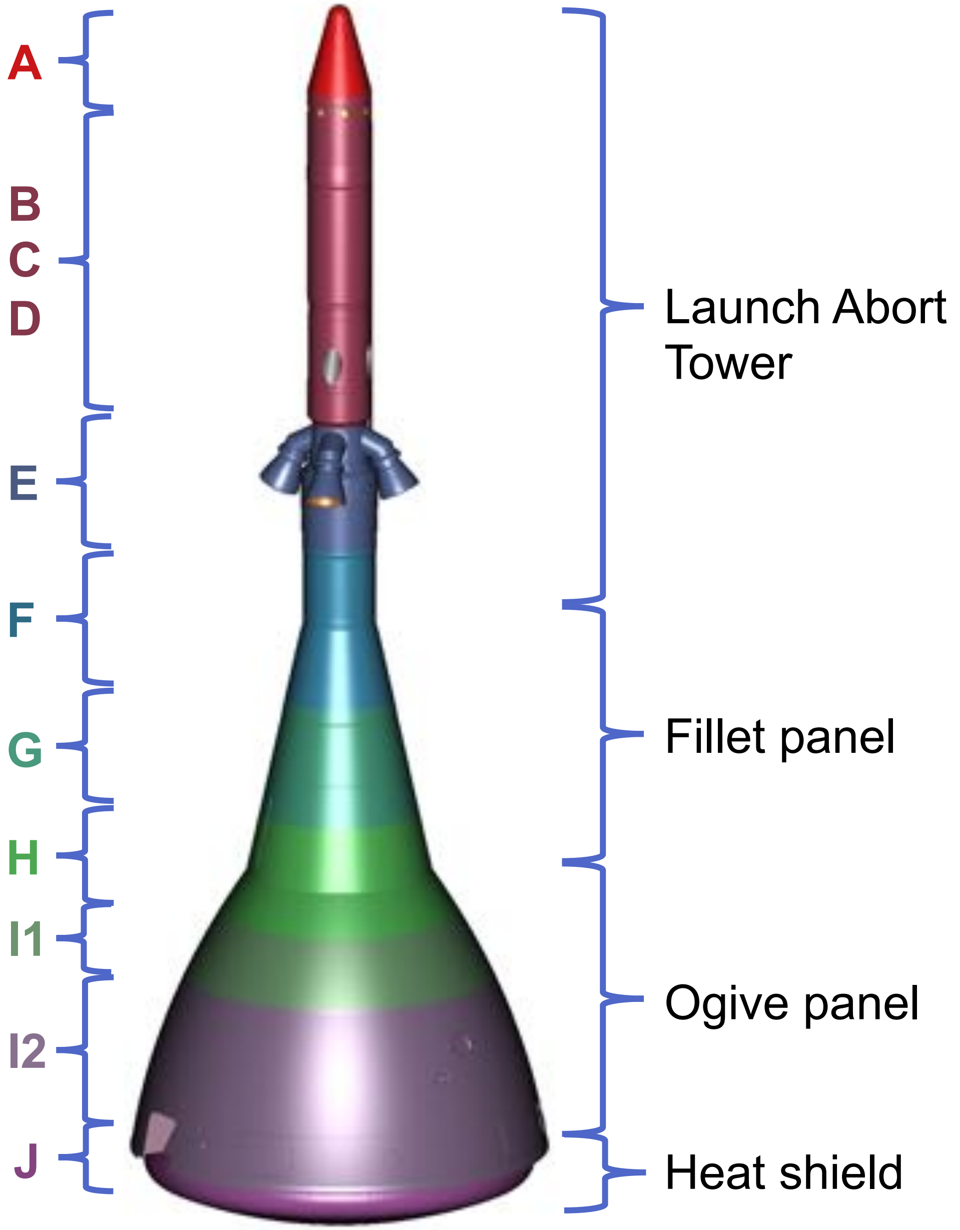
HPC Resources (FY18)	
Wallclock time (days)	18
Number of nodes	80
Node type	Skylake
Total number of cores	3,200
Time simulated (seconds)	0.5
Volume data (TB)	100

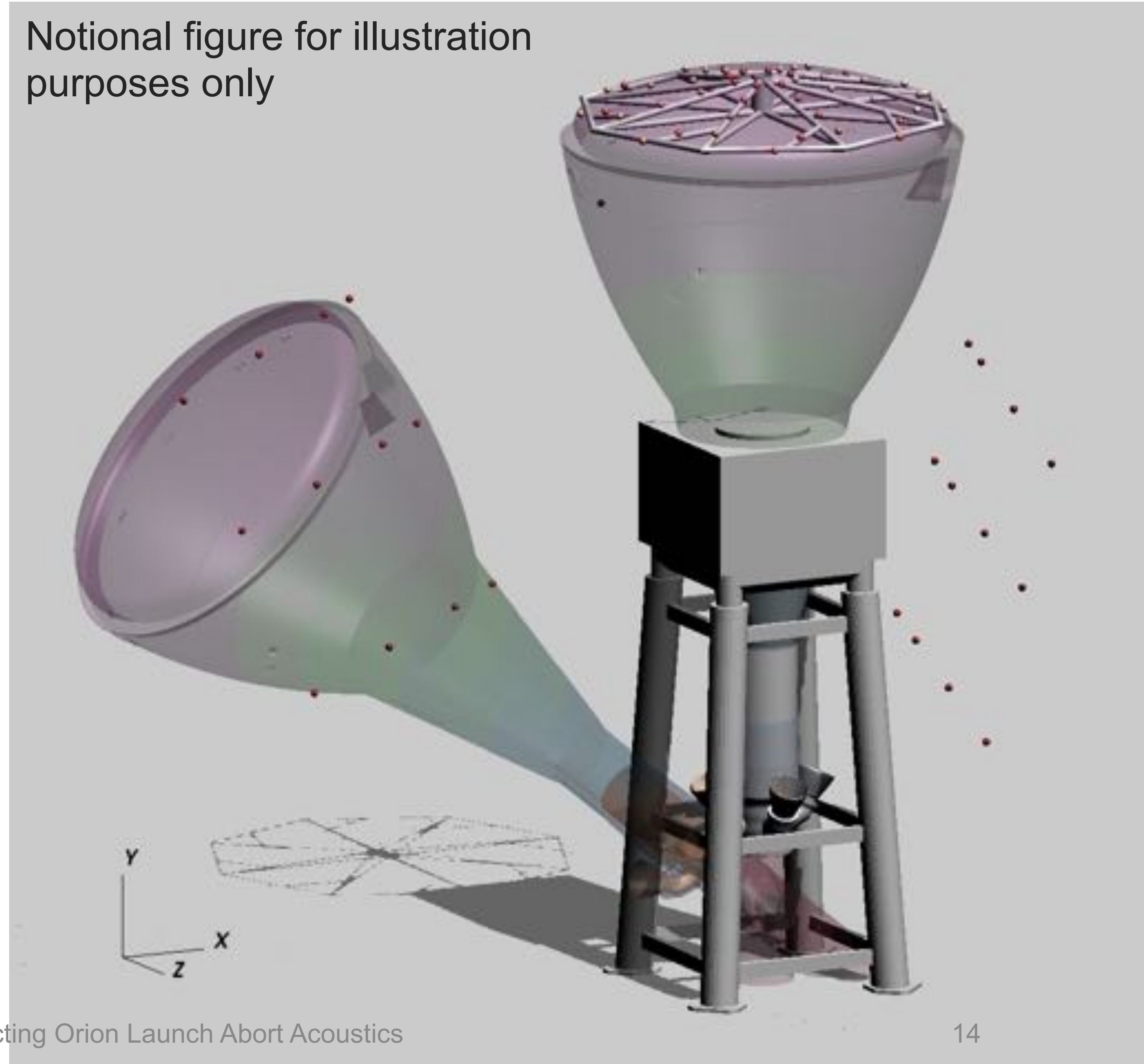
Rendering of the Orion Launch Abort System (LAS) qualification ground test (QM1) simulated using LAVA Cartesian with adaptive mesh refinement (AMR). Video showcases the turbulent structures resolved in the plumes colored by gauge pressure. Each pixel turning from blue to white to red indicates an acoustic waves passing through that can impinge on the apparatus and cause vibrations. We provided loads on heat shield fixture and crane to help test designers ensure safety of the test and reduce risk in data collection.

QM-1 Ground Test Video

Link: https://youtu.be/B-1qajOvEI4

Orion LAS Surface Acoustic Zones





Acoustics Post-Processing

Procedure is identical between exp test data and CFD predictions

Obtain pressure time $p(t)$ series excluding ignition over-pressure signature

Use Welch method to compute power spectral density (PSD) $S_{xx}(f) = \hat{p}(f)\hat{p}^*(f)$ with segment length ΔT_{seg}, 50% overlap, and Hann window

Perform spatial average of PSD from different sensors within each acoustic zone

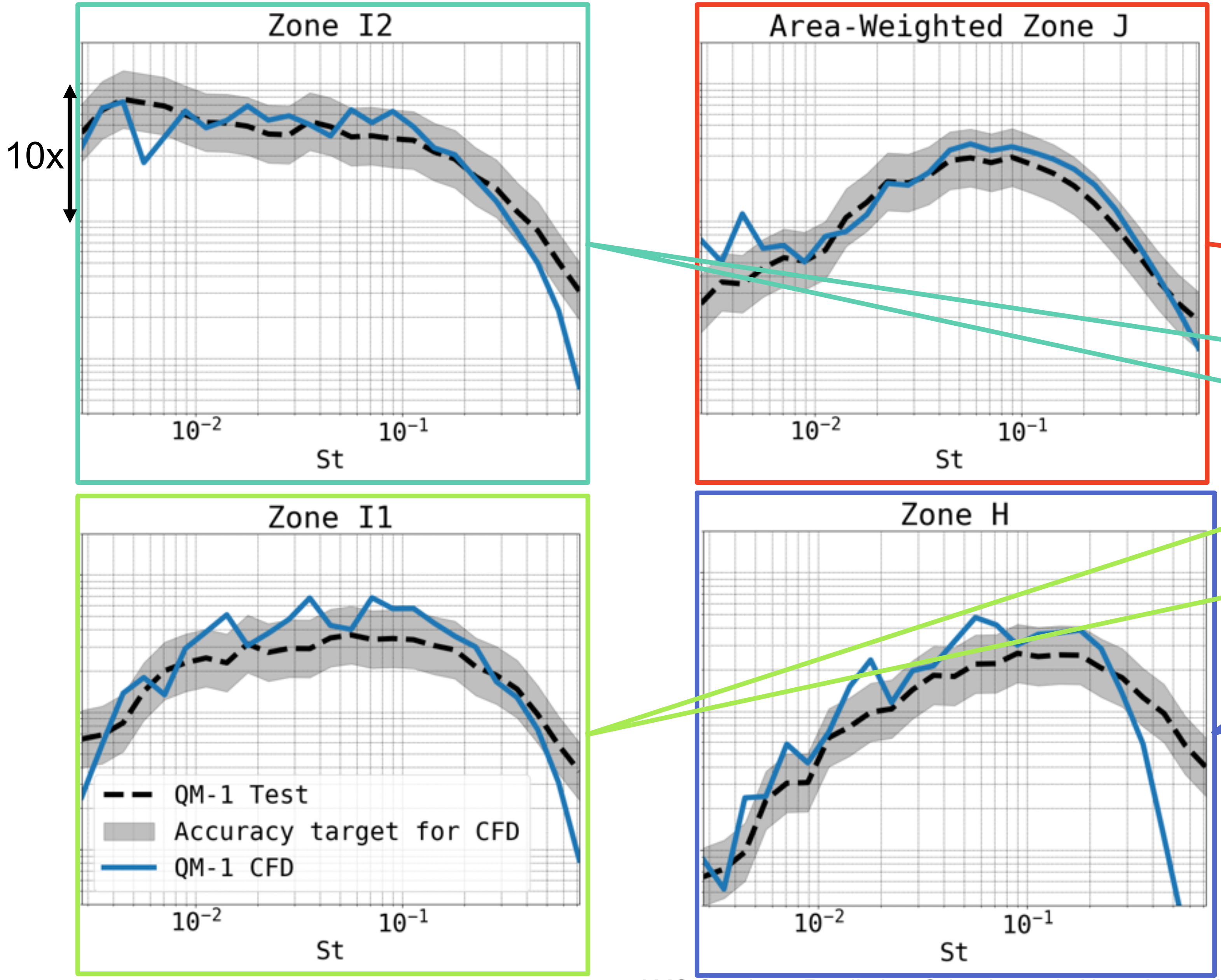
Perform third octave band-filter to reduce data complexity and produce smoother spectra

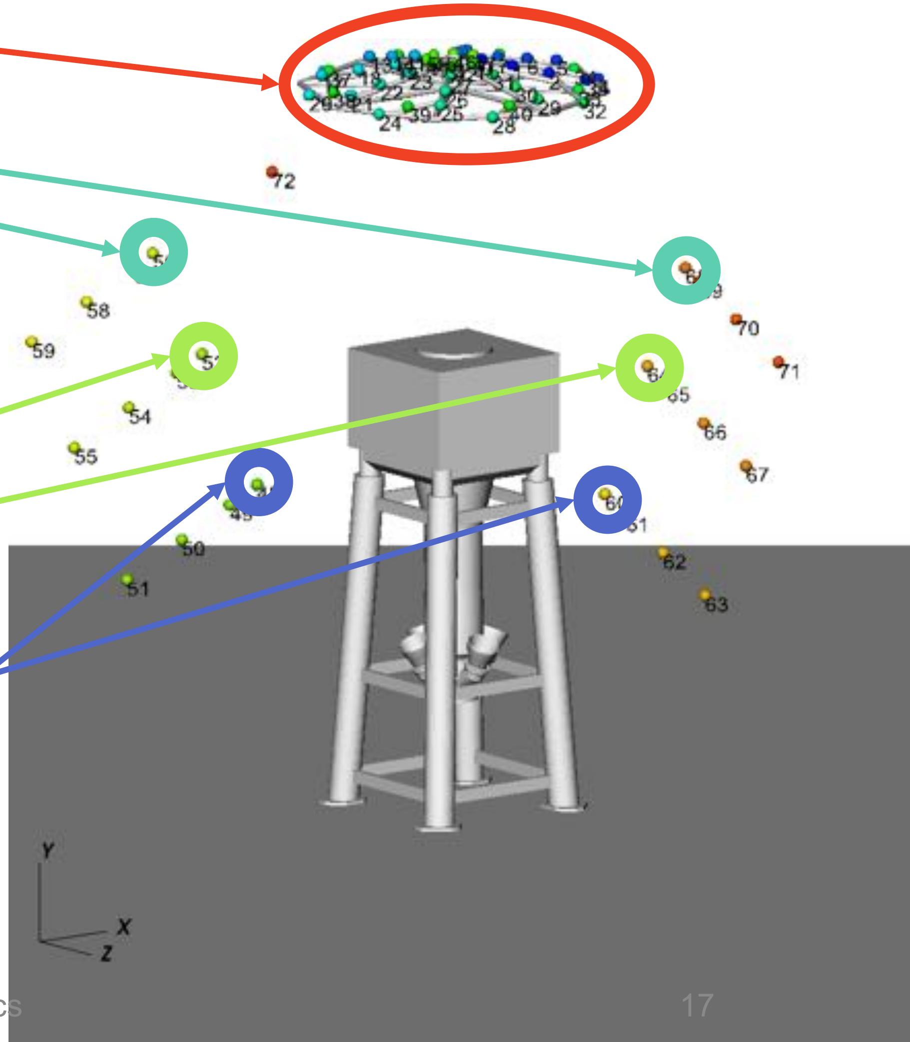
Presenting ITAR data

- For those of you who work with NASA: full Technical Project Report titled “Computational Aero-Acoustic Simulations Of The Orion Launch Abort Vehicle” is available on NTRS with ID#20210025053
- All plots will show apples-to-apples comparisons between CFD and test data, but all data is normalized by values not made public
- Specifically:
  - Distances if shown will all be normalized by D: the nozzle exit diameter
  - Strouhal number instead of frequency: $St = f\left(\frac{D}{U}\right)$, where U is the area-averaged nozzle exit velocity (unknown to public)
  - Spectra will be non-dimensionalized by nozzle exit dynamic pressure (unknown to public): $S_{xx}^{*} = S_{xx}\left(\frac{U}{D}\right)\left(\frac{1}{q_e^2}\right)$
  - Spectra may be further scaled by ratios of total or dynamic pressure to investigate scaling laws (individual q_{∞} values will not be shared)

QM-1 Abort Motor Test Validation

Caveat
QM-1 CFD duration: 0.53s
QM-1 Test duration: 2.52s





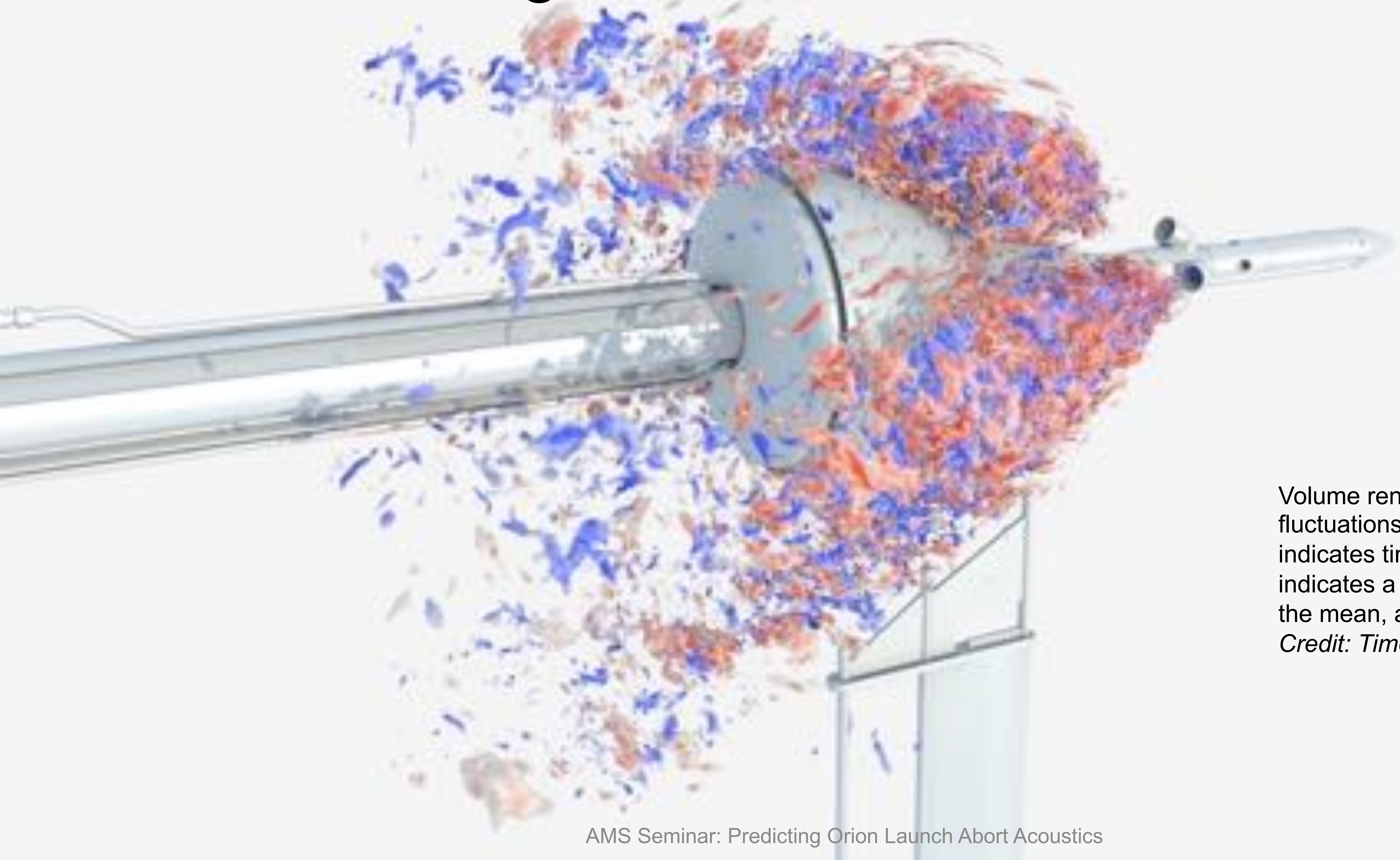
Launch Abort Scenarios

CAD Model	Freestream Mach Number	Freestream Total Pressure Ratio	Angle of Attack	Sideslip Angle	CFD Acoustic Interval Length (s)	Test Acoustic Interval Length (s)
QM-1	0	1.00	Small	Small	0.423	2.4
EM-1	0	1.20	Small	Small	0.422	N/A
EM-1	1.15	0.72	Small	Small	0.293	N/A
EM-1	1.6	0.52	Small	Small	0.282	N/A
EM-1	0.7	0.75	Large	Large	0.290	N/A
EM-1	0.7	0.75	Large	Small	0.261	N/A
EM-1	0.69	1.39	Large	Large	0.704	N/A
80-AS	0.7	0.93	Large	Large	*0.090	5.0
PA-1	0	1.04	Small	Small	0.476	2.4
PA-1	0→0.4	1.15	Small→Large	Small→Large	1.156	2.4
AA-2	1.17	0.71	Small	Small	0.520	2.4
AA-2	1.62	0.89	Small	Small	0.500	2.4
AA-2	4.36	0.01	Small	Small	0.500	N/A
AA-2	1.17	0.99	Small	Small	0.869	N/A

Subject of previous AMS seminar titled: “Orion Launch Abort System Acoustics”

*tunnel scale model

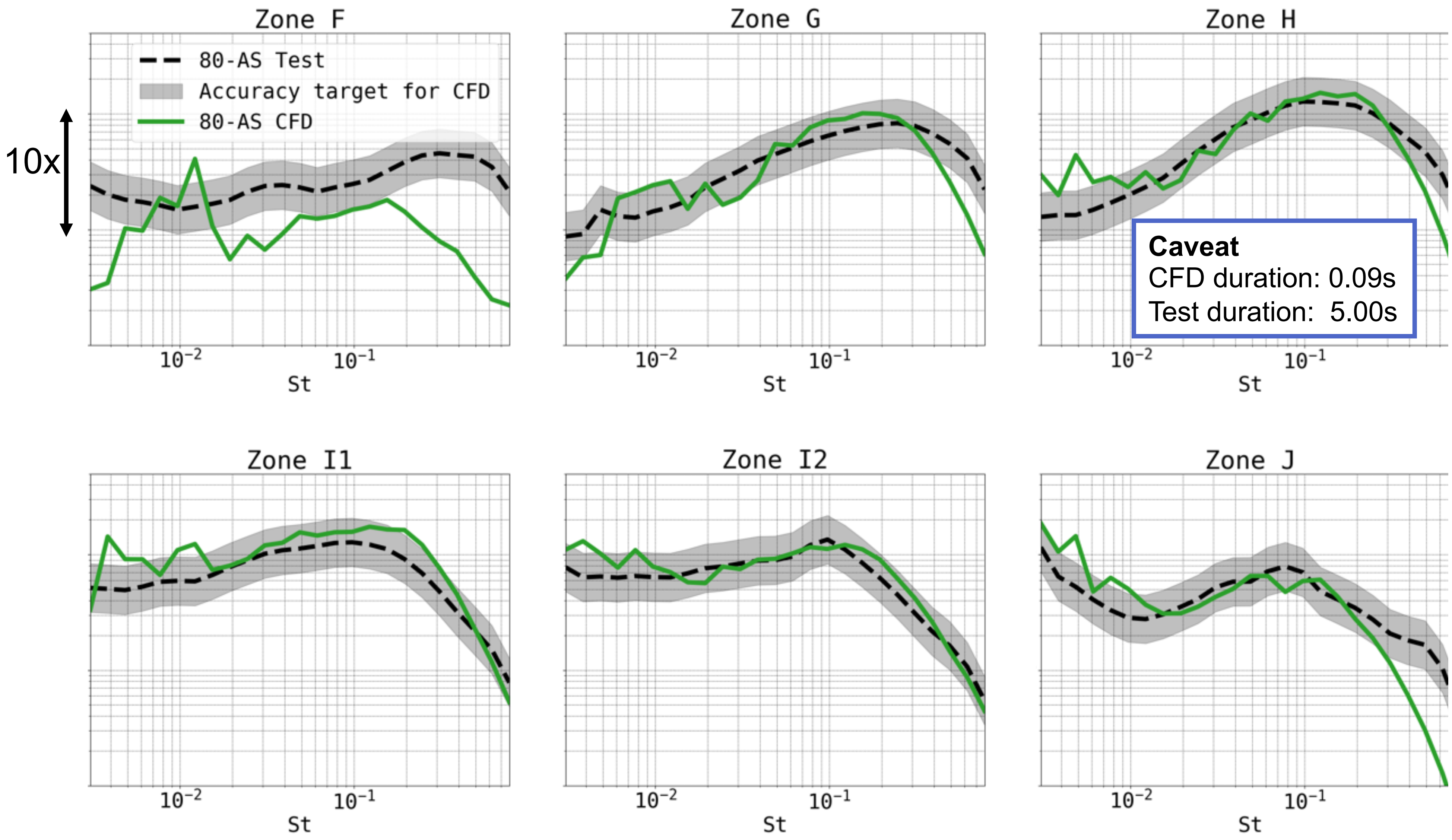
Transonic High AoA Wind Tunnel Simulation

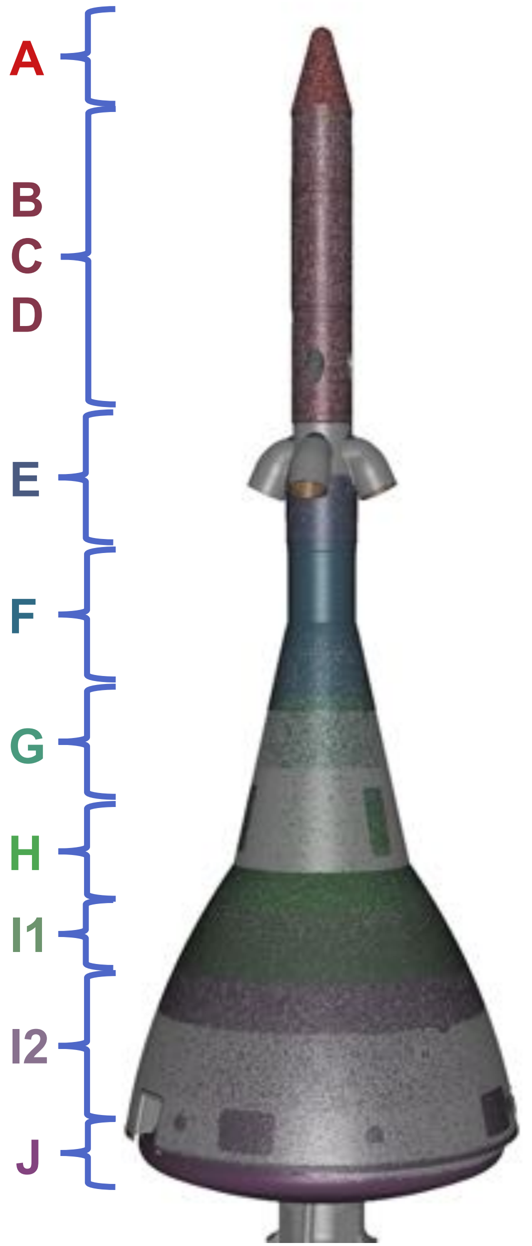


Volume rendering of large pressure fluctuations p’ = p - <p> where < > indicates time-average. Blue indicates a negative deviation from the mean, and red a positive one. *Credit: Timothy Sandstrom*

Transonic High AoA Wind Tunnel Validation

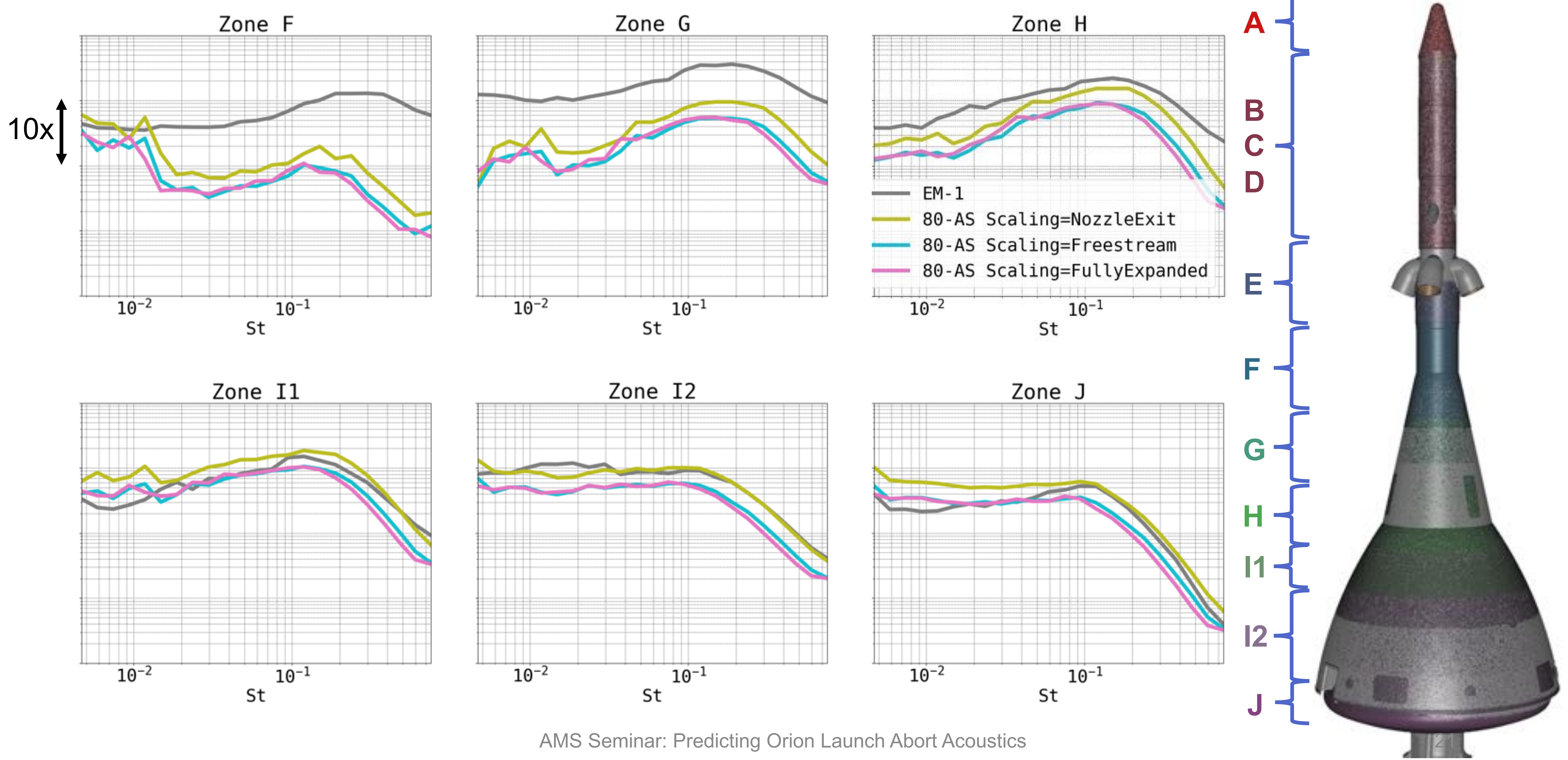
Arithmetic average of PSD of all sensors in each zone





Scaling CFD Spectra From Wind Tunnel To Flight

Area-weighted average of PSD in each zone across all points in surface mesh



Pad Abort Flight Test

- Date: May 6, 2010
- Vehicle: Orion MPCV mockup with LAS Tower, but no fillet or ogive fairing, only structural connector
- Trajectory: Accelerates from rest on ground to 10x earth's gravity in 0.5 seconds, reaches Mach 0.7 toward end of abort motor burn.
- Link: https://www.youtube.com/watch?v=h8AXwtC-u28&t=59s

Pad Abort Flight Test Simulation

Video shows cut of Cartesian boxes (each contain 16^3 cells) and fine mesh tracking PA-1 vehicle (green) as it accelerates away from the ground. Gauge pressure is also shown on cut plane: blue is low, red is high.

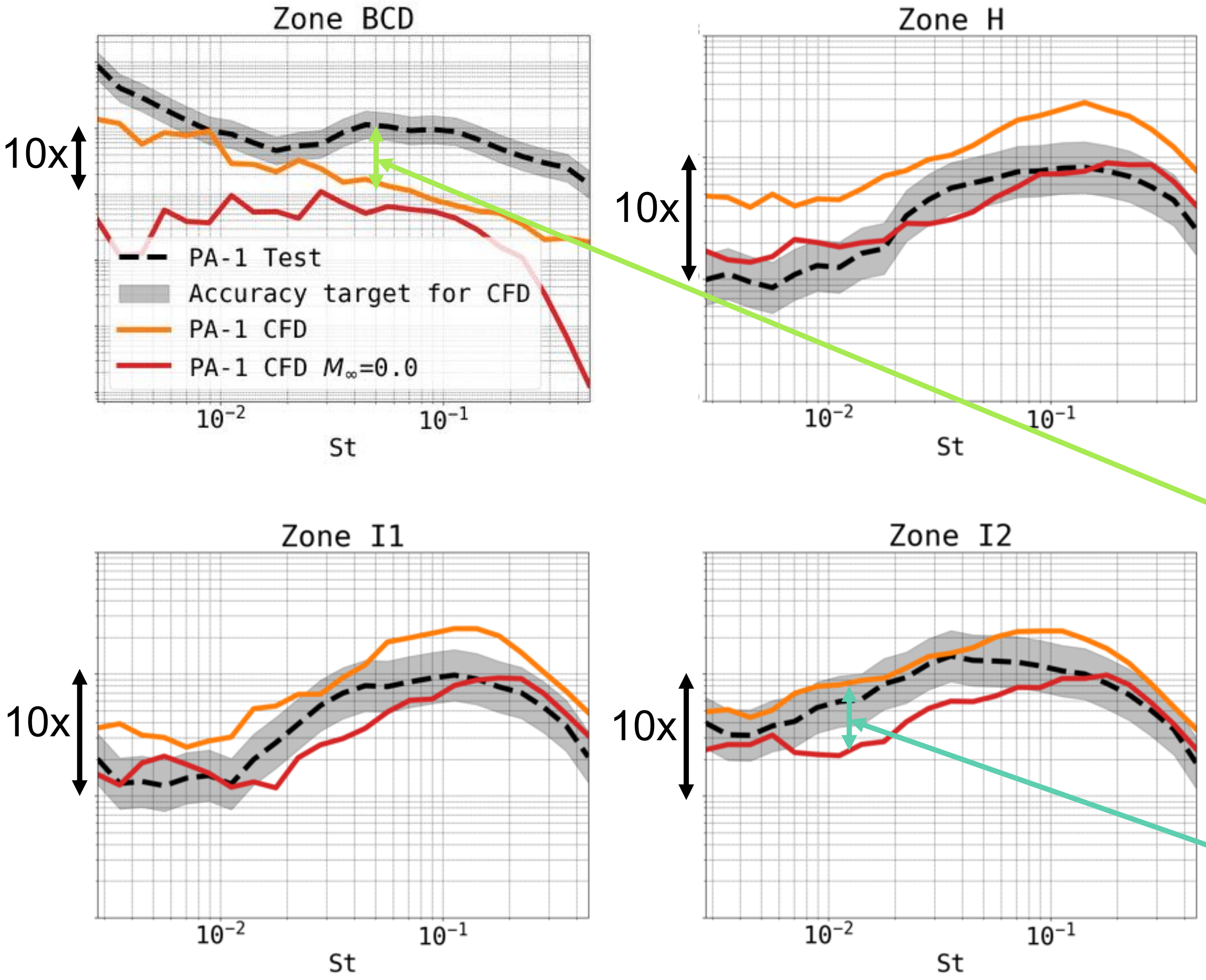
HPC Resources (FY19)	
Wallclock time (days)	45
Number of nodes	400
Node type	Skylake
Total number of cores	16,000
Time simulated (seconds)	1.25
Volume data (TB)	200

Pad Abort Flight Test Simulation

Video shows passive particles seeded at the nozzle colored by velocity magnitude: white is fast, dark orange is slow

Pad Abort Flight Test Validation

Arithmetic average of PSD of all sensors in each zone

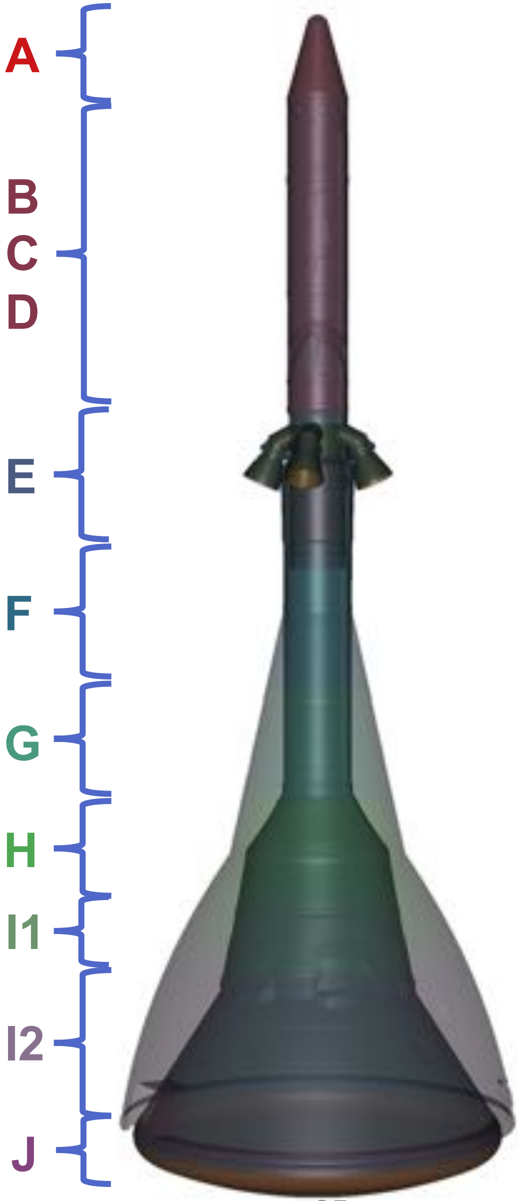


Caveat

Case	Duration (s)
Flight Test	2.50
CFD Accel	1.16
CFD $M_\infty = 0$	0.48

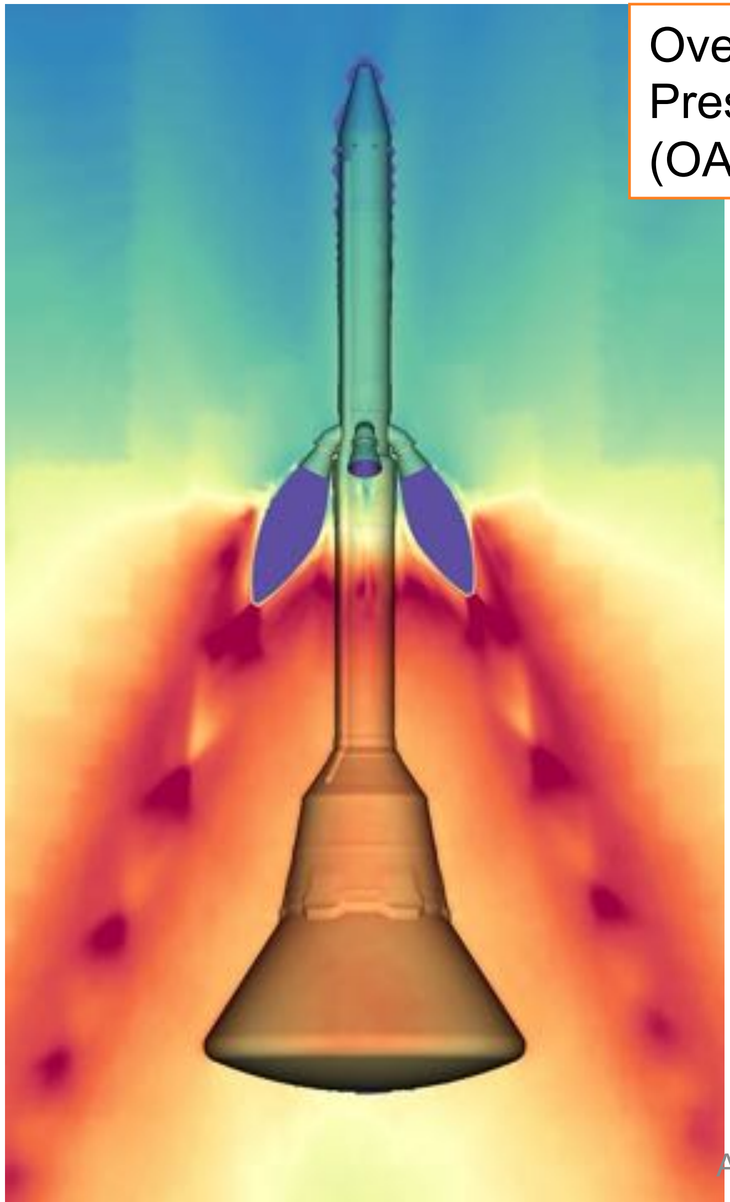
Attitude Control Motors are **not** modeled

Effect of acceleration



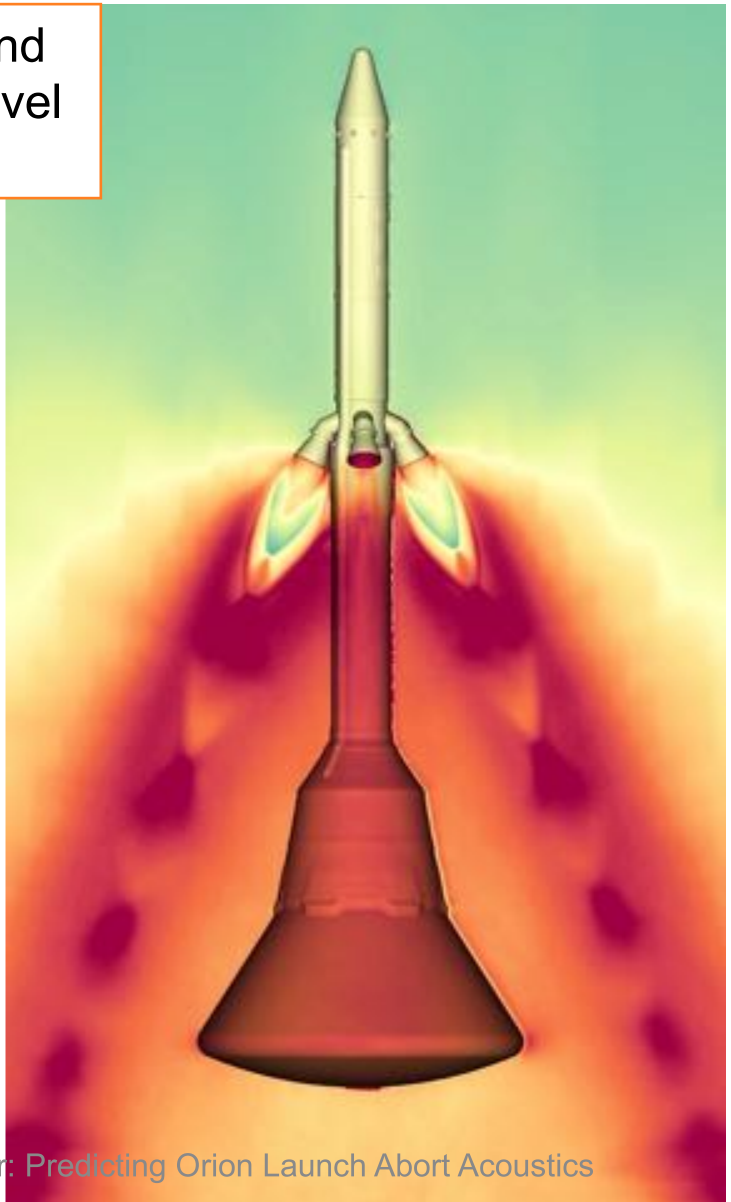
PA-1 Effect of Acceleration on Acoustics

PA-1 CFD $M_\infty = 0$



Overall Sound Pressure Level (OASPL)

PA-1 CFD



Vehicle acceleration caused more fluctuations inside combustion chamber and at nozzle exit, which persist downstream.

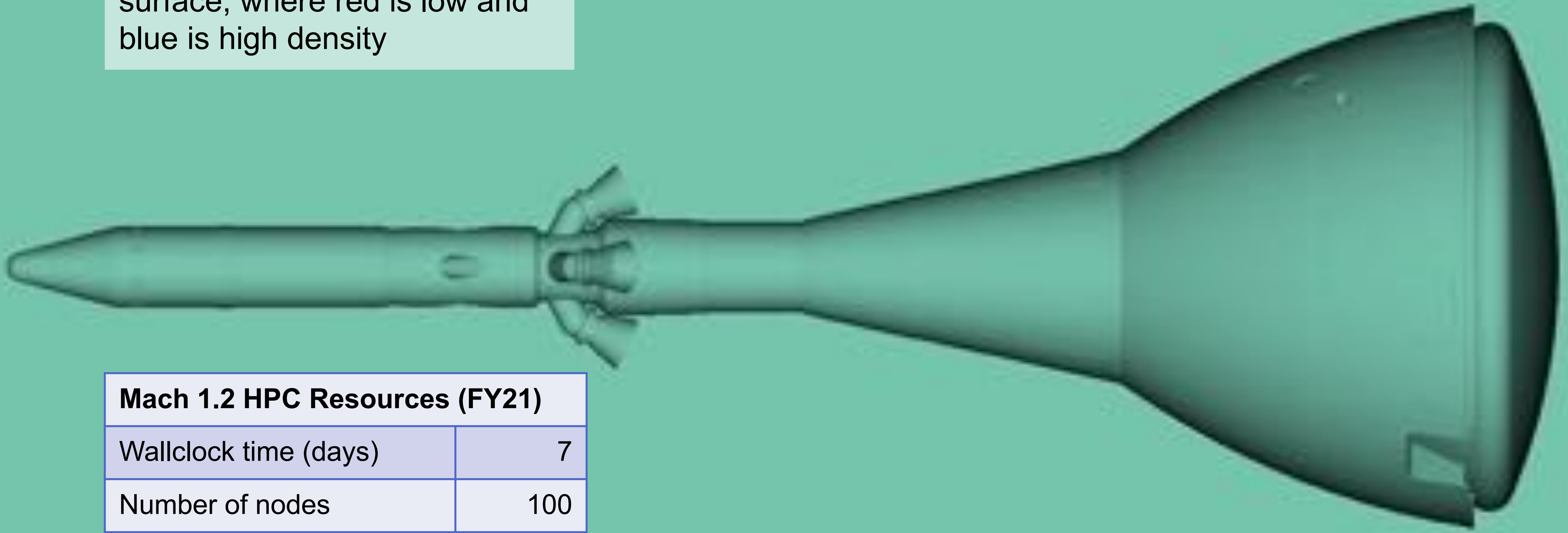
We have not yet been able to tease apart what percentage of these added fluctuations are due to the physics of acceleration versus spurious acoustics due to immersed boundary method when the vehicle is moving with respect to the Cartesian background grid.

Ascent Abort Flight Test (AA-2)

- Date: July 2, 2019
- Vehicle: Launch abort vehicle atop Northrop Grumman provided booster
- Trajectory: Abort occurs at Mach 1.17 and accelerates to Mach 1.6
- Link: https://youtu.be/4rfsDMGplZU

AA-2 Mach 1.2 Simulation

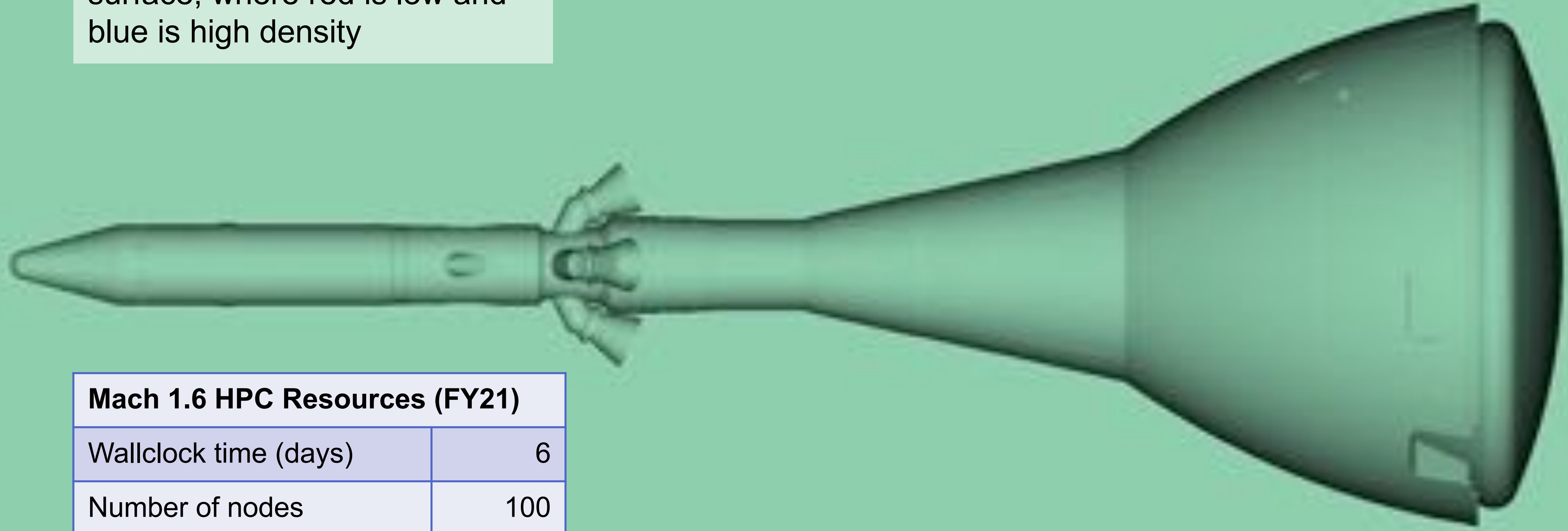
Video from AA-2 Mach 1.17 simulation: logarithm of density on the cut plane and vehicle surface, where red is low and blue is high density



Mach 1.2 HPC Resources (FY21)	
Wallclock time (days)	7
Number of nodes	100
Node type	Rome
Total number of cores	12,800
Time simulated (seconds)	0.58
Volume data (TB)	100

AA-2 Mach 1.6 Simulation

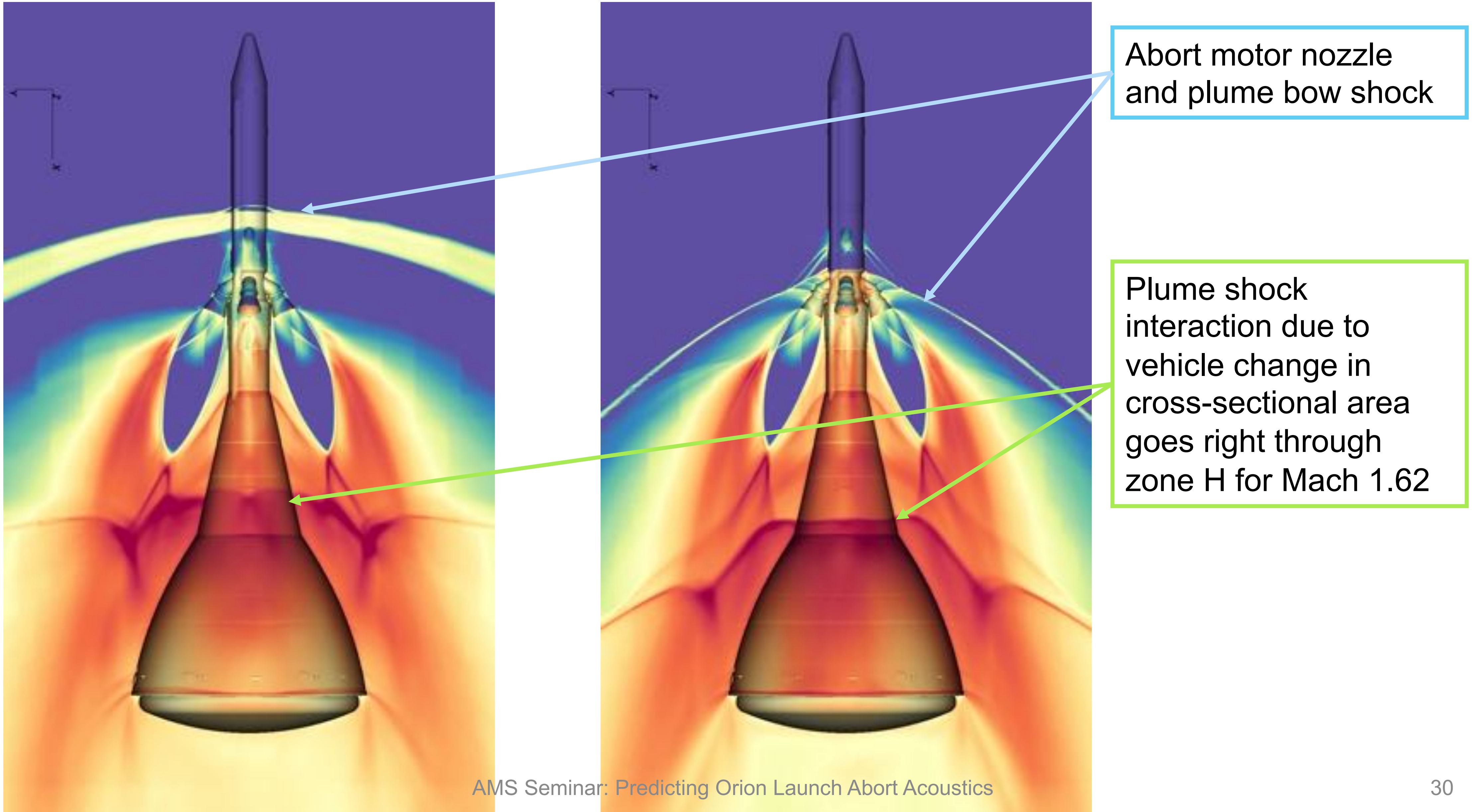
Video from AA-2 Mach 1.615 simulation: logarithm of density on the cut plane and vehicle surface, where red is low and blue is high density



Mach 1.6 HPC Resources (FY21)	
Wallclock time (days)	6
Number of nodes	100
Node type	Rome
Total number of cores	12,800
Time simulated (seconds)	0.51
Volume data (TB)	100

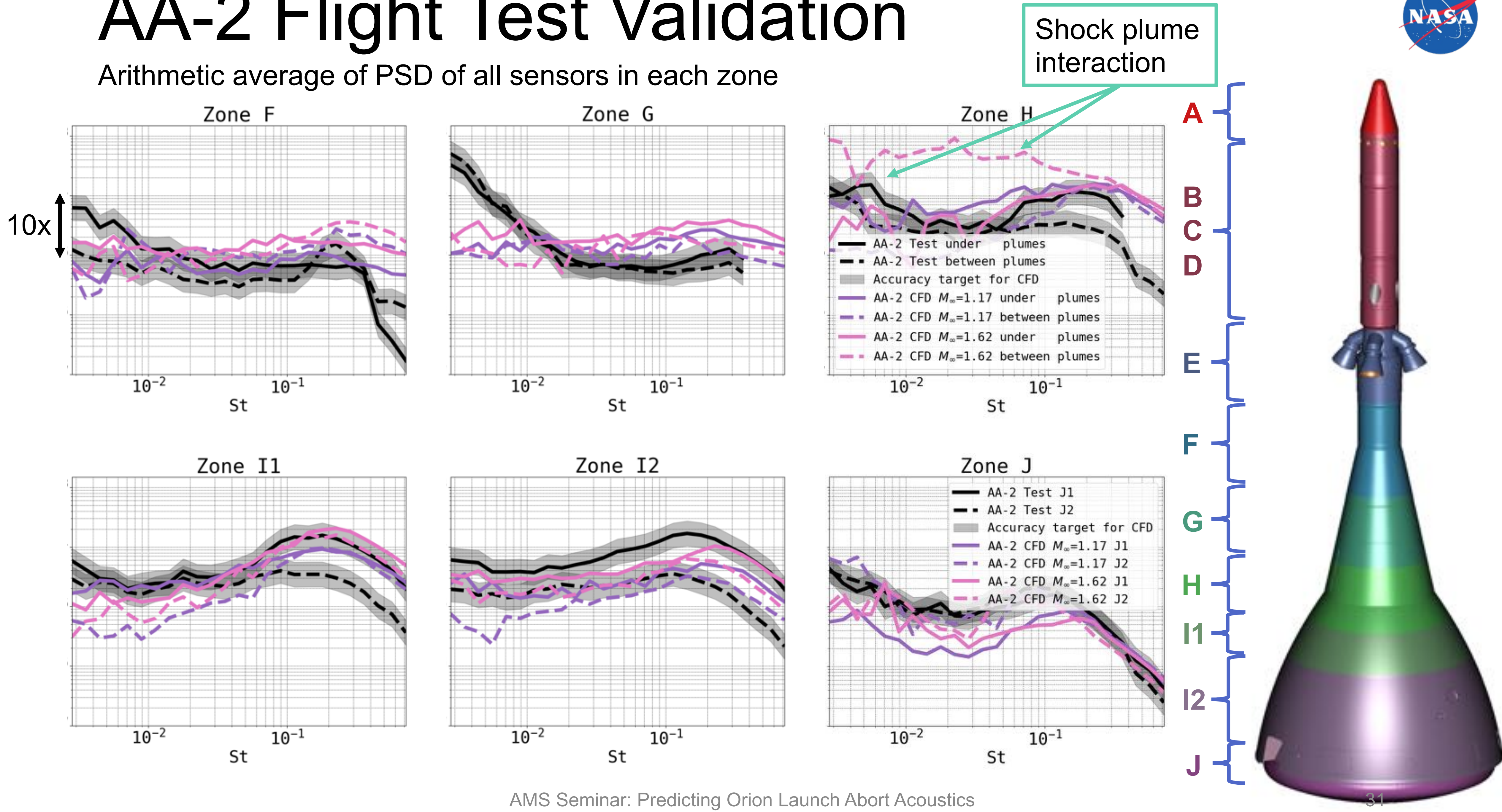
Effect of Mach Number on OASPL

AA-2 CFD M_∞ =1.17 AA-2 CFD M_∞ =1.62

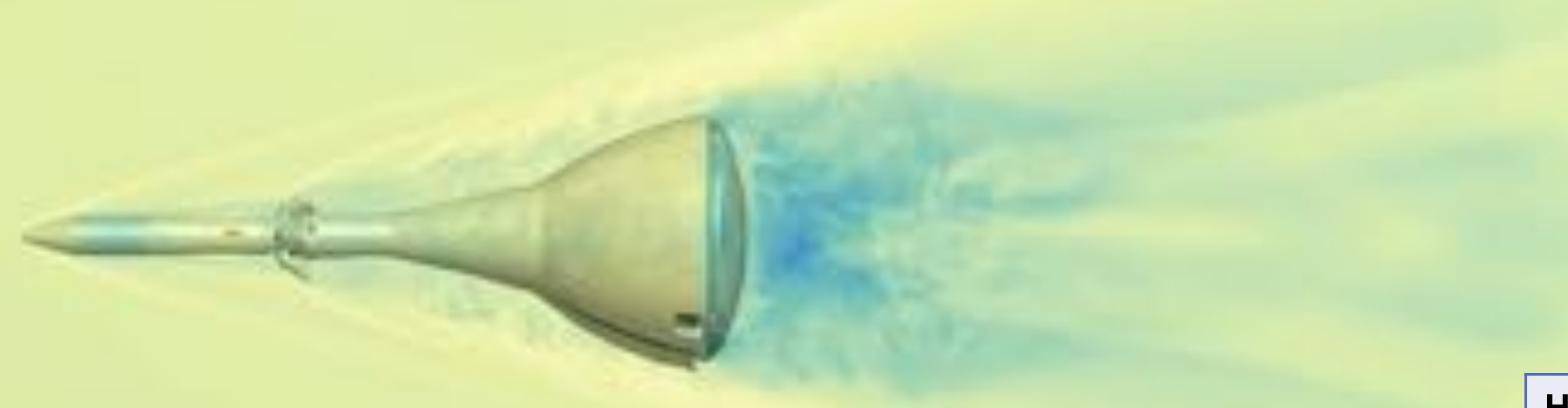


AA-2 Flight Test Validation

Arithmetic average of PSD of all sensors in each zone



High Altitude Supersonic Abort Simulation

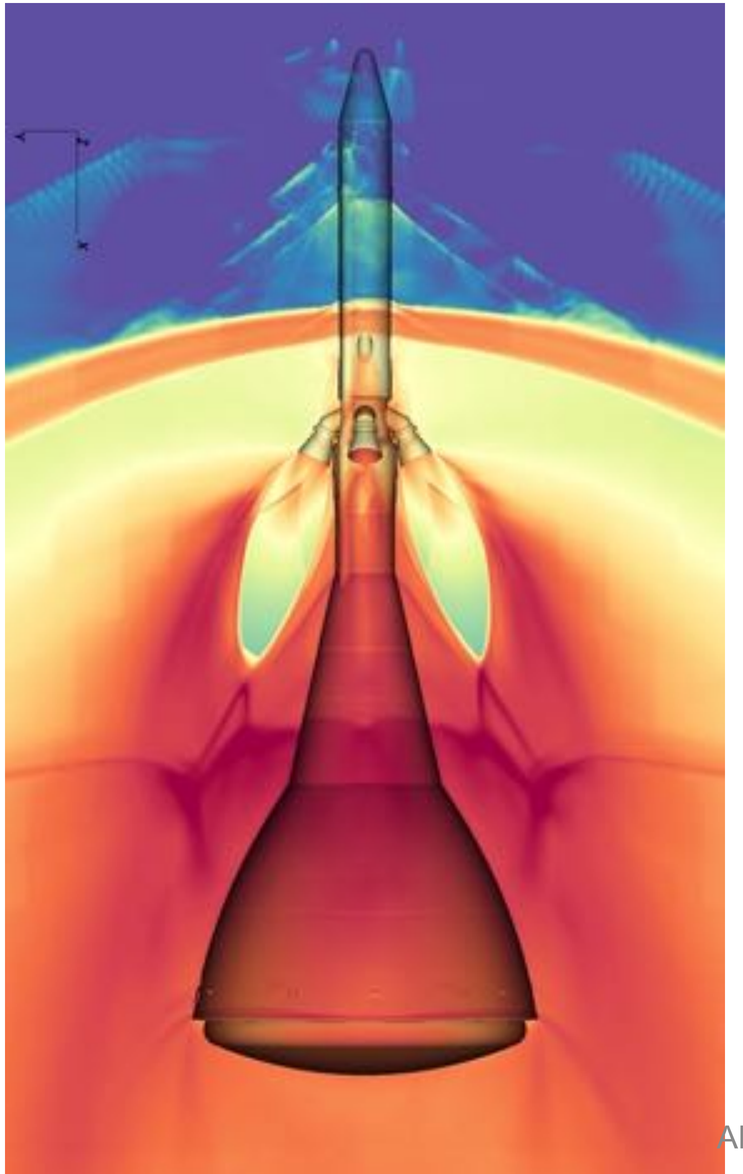


Video from AA-2 Mach 4.3 high altitude simulation: logarithm of density on the cut plane and vehicle surface, where red is high and blue is low density

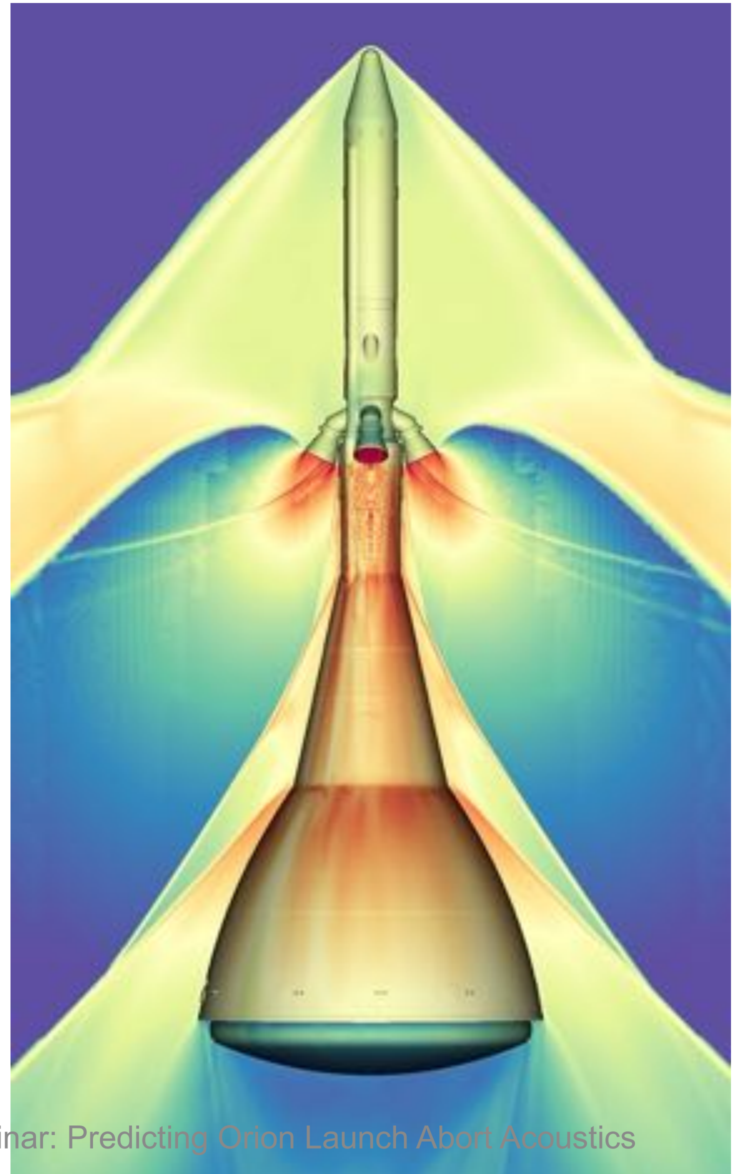
HPC Resources (FY21)	
Wallclock time (days)	14
Number of nodes	100
Node type	Rome
Total number of cores	12,800
Time simulated (seconds)	0.52
Volume data (TB)	200

Effect of High Altitude on OASPL

AA-2 CFD $M_\infty = 1.17$



High Altitude CFD $M_\infty = 4.3$

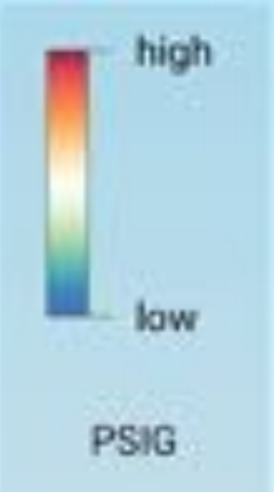


Due to low air pressure at high altitude, the plumes are extremely under-expanded and grow to encompass the entire LAV. Free shear layer instability is suppressed and acoustics are reduced significantly across entire vehicle.

Supersonic Low Altitude Abort

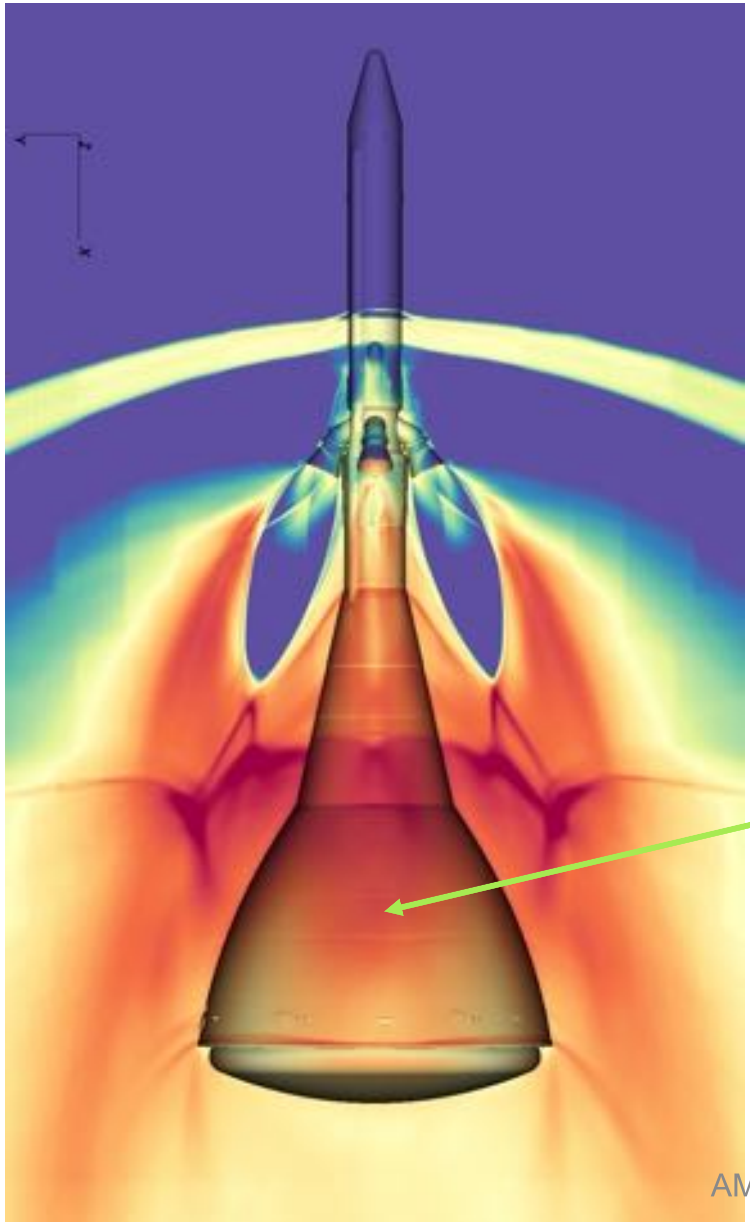
Passive particles seeded at nozzle exit and vehicle surface both colored by pressure.
Video credit: Tim Sandstrom

HPC Resources (FY21)	
Wallclock time (days)	10
Number of nodes	105
Node type	Skylake
Total number of cores	4,200
Time simulated (seconds)	0.84
Volume data (TB)	170

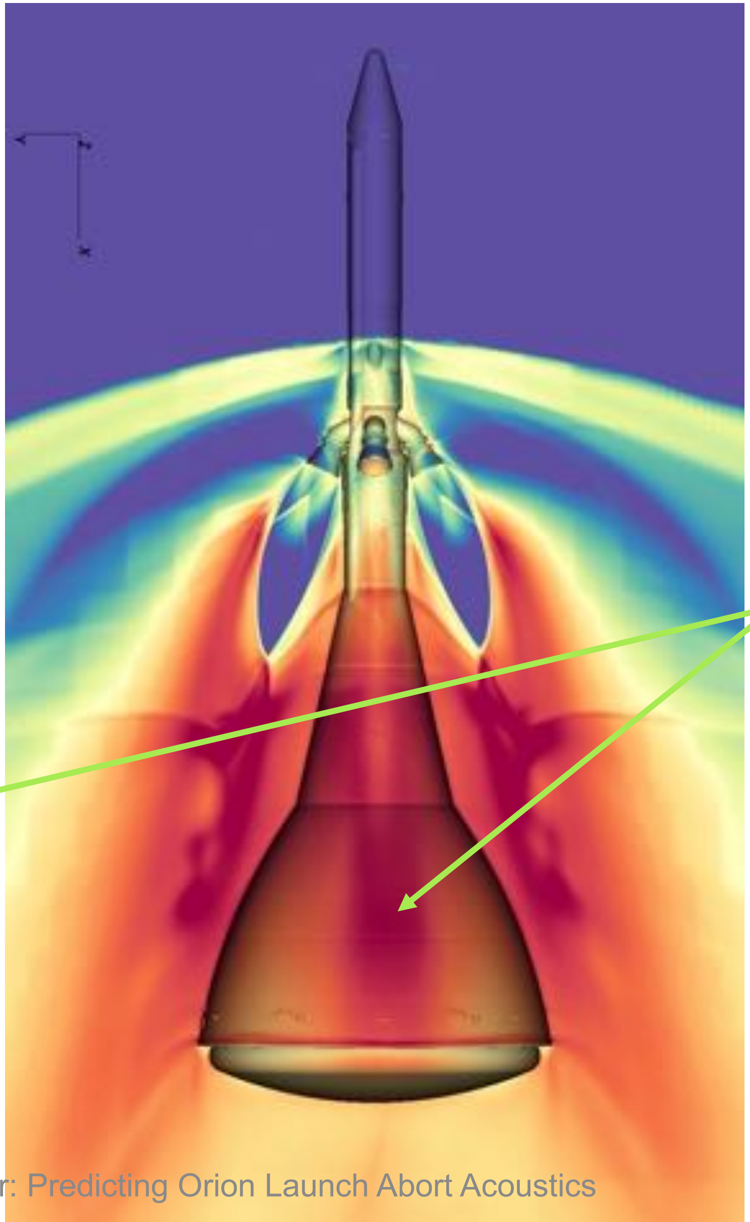


Effect of Lower Altitude For Supersonic Abort

AA-2 CFD $M_\infty = 1.17$



Low Altitude CFD $M_\infty = 1.17$

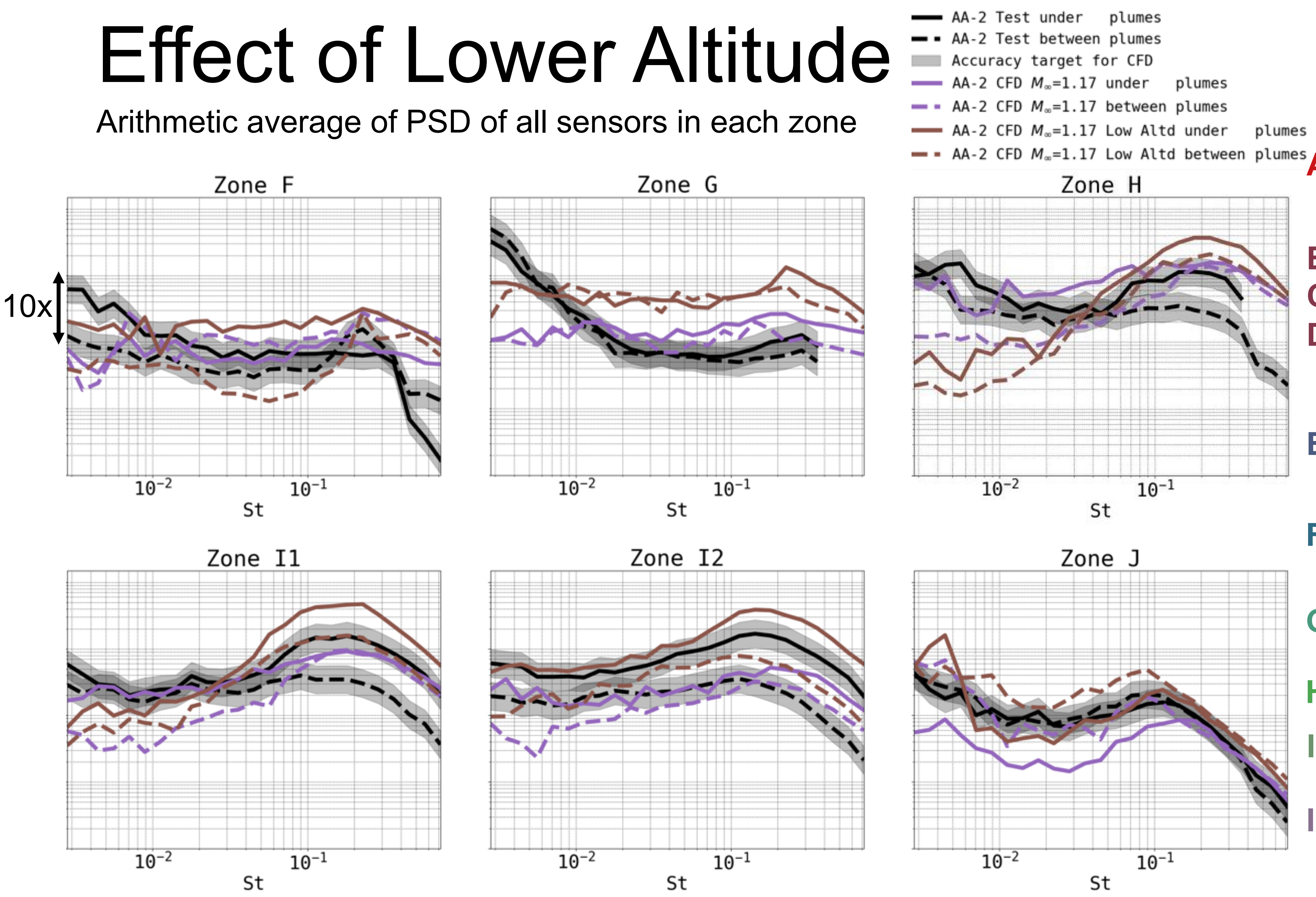


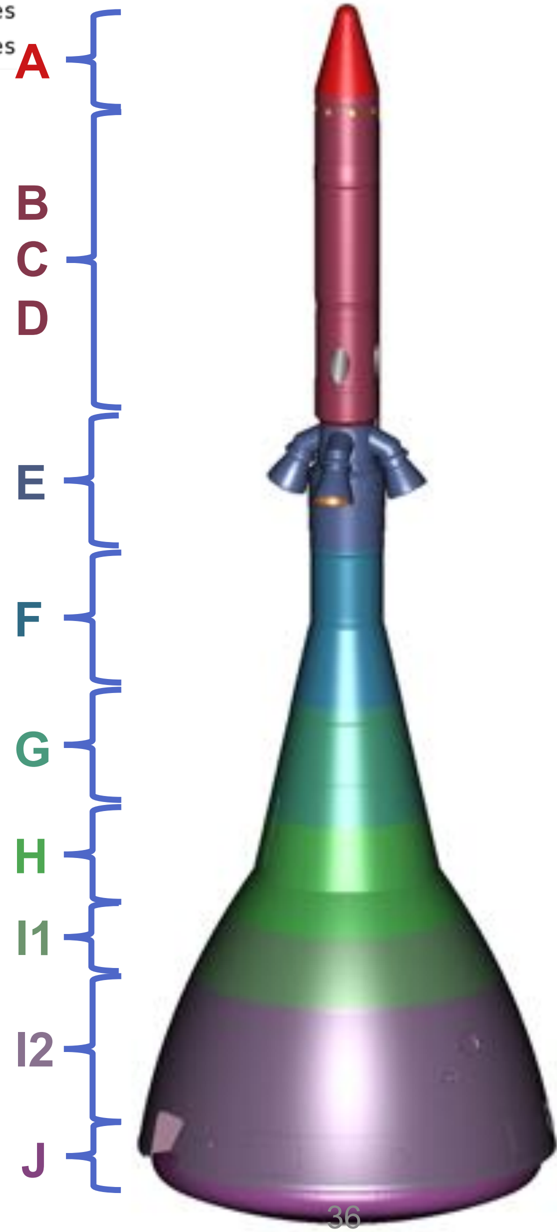
Both plots show OASPL with the same colormap settings for direct comparison

Increasing freestream dynamic pressure pushes the plumes closer to the vehicle and increases strength of fluctuations (most visibly under the plumes).

Effect of Lower Altitude

Arithmetic average of PSD of all sensors in each zone

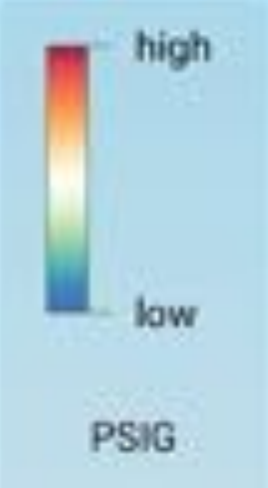




Low Altitude High AoA Transonic Abort

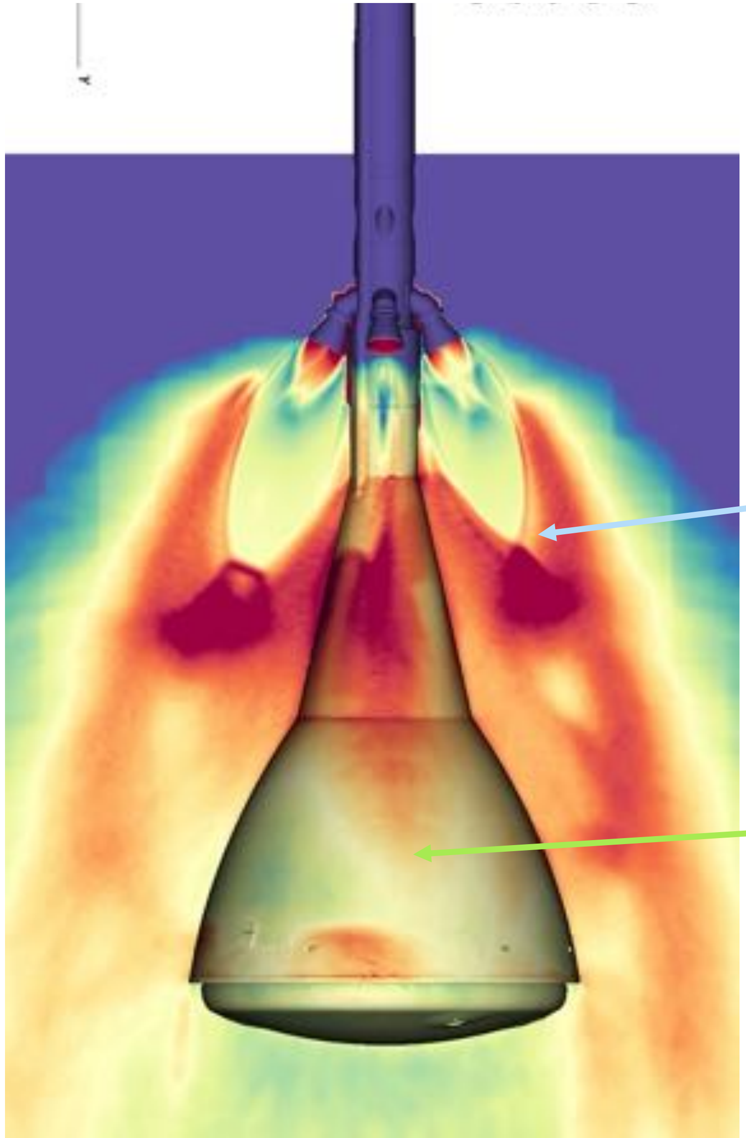
Passive particles seeded at nozzle exit and vehicle surface both colored by pressure. Video credit: Timothy Sandstrom

HPC Resources (FY21)	
Wallclock time (days)	10
Number of nodes	106
Node type	Skylake
Total number of cores	4,240
Time simulated (seconds)	0.53
Volume data (TB)	120

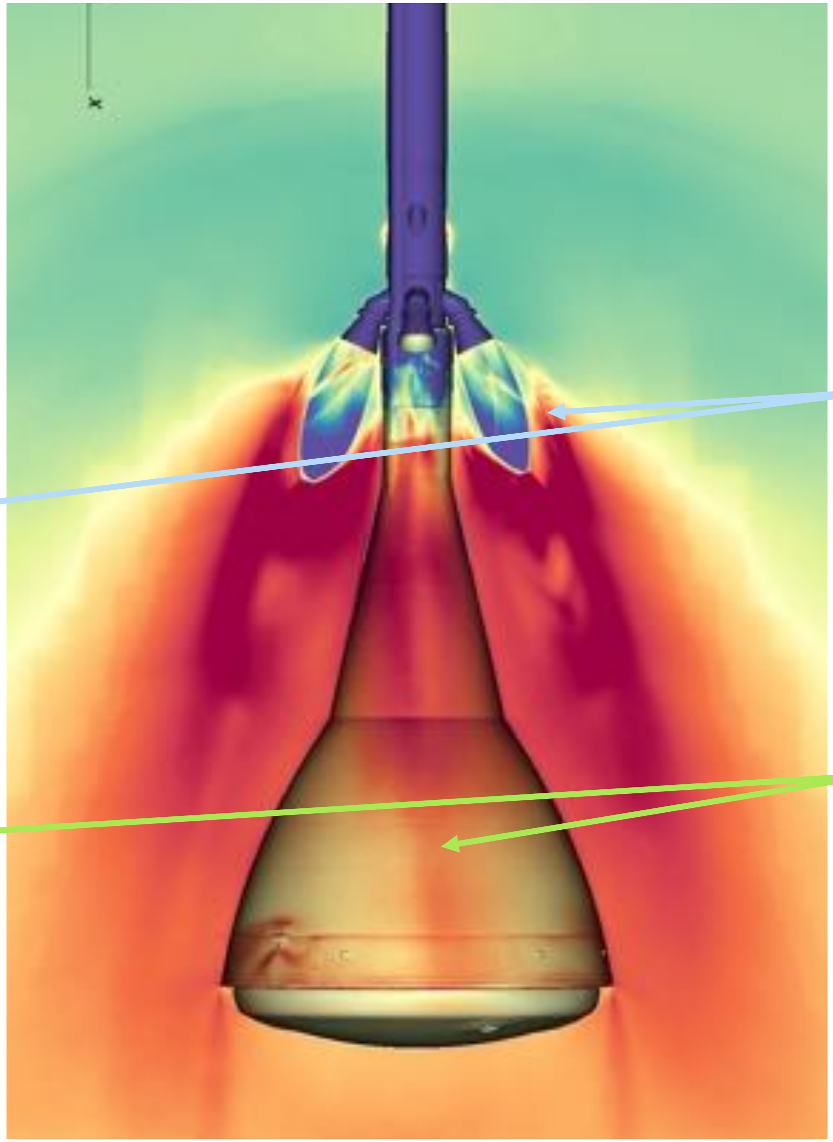


Effect of Lower Altitude For Transonic Abort

CFD $M_\infty = 0.7$



Low Altitude CFD $M_\infty = 0.7$



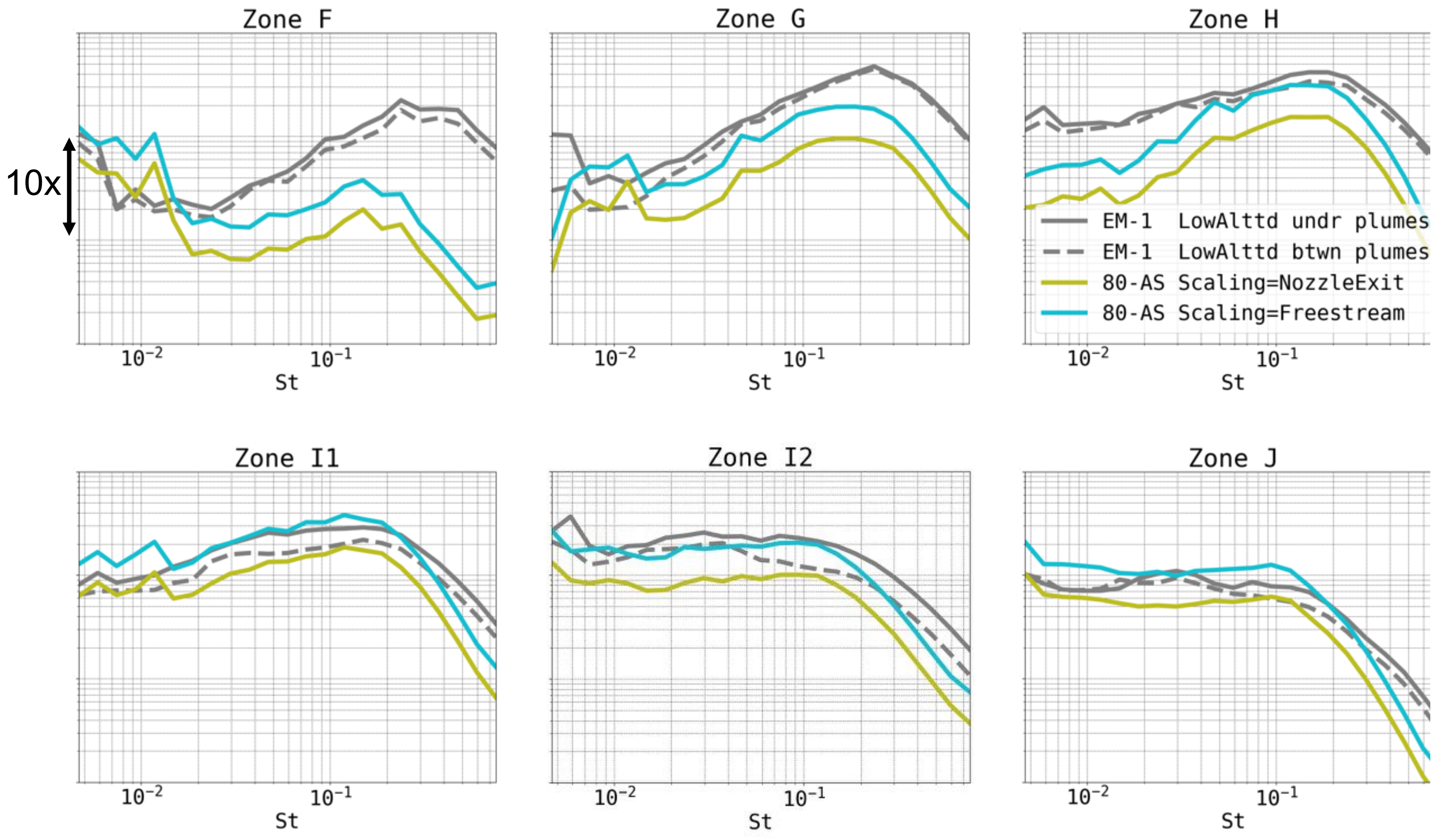
Both plots show OASPL with the same colormap settings for direct comparison

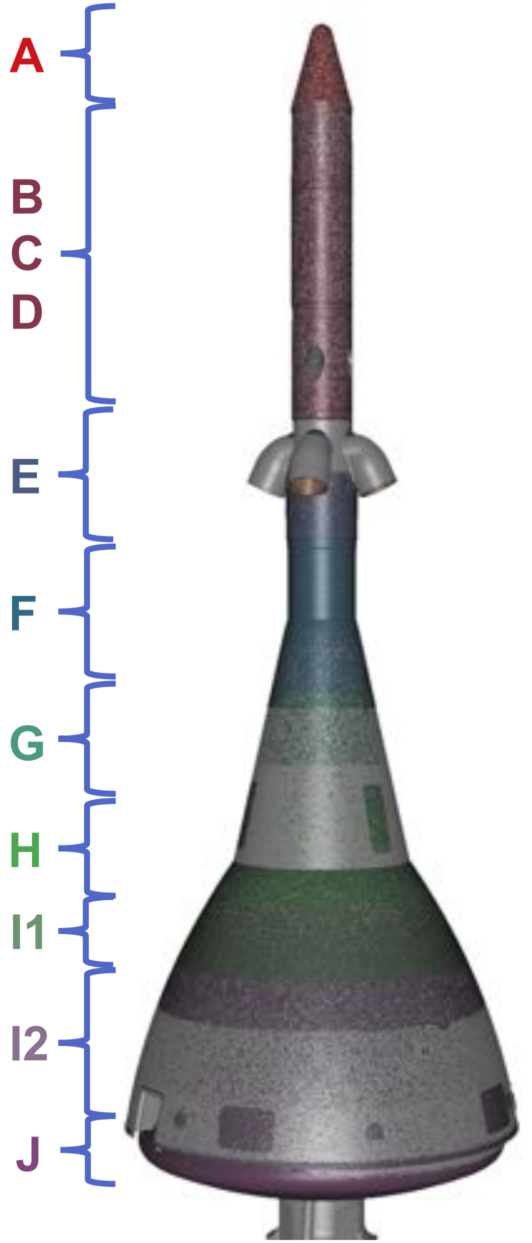
Abort motor plume size changes drastically with altitude below supersonic regime

Increasing freestream dynamic pressure pushes the plumes closer to the vehicle and increases strength of fluctuations (most visibly under the plumes).

Scaling CFD Spectra From Wind Tunnel To Flight

Area-weighted average of PSD in each zone across all points in surface mesh





Impact to Orion project

- After achieving the accuracy target for CFD across wide range of Strouhal numbers for subsonic and transonic abort scenarios, CFD predictions are being integrated into the database of wind tunnel, ground, and flight test data to help refine best estimates for environment

- CFD helped answer more definitively questions regarding how to best scale wind tunnel data to flight

- CFD also shows that a single scaling parameter will not work well when accounting for altitude changes for supersonic aborts because shock-plume interactions may move from one acoustic zone to another

Outlook

In order to achieve accuracy target for supersonic abort AA-2 simulations across all zones of interest, need improvements in:

- Attitude Control Motor (ACM) modeling: for subsonic and transonic abort, the ACM jets are unlikely to have a substantial impact, but for supersonic it changes the mean flow field by changing the strength and location of the bow shock at the nose of the vehicle (also implies downstream shock locations will change)
- Wall shear-stress modeling: at supersonic speed, the interactions of plumes and shocks with thin attached boundary layers is expected to give rise to regions of separated re-circulating flow
- Modeling turbulence inside nozzle: could improve delay in transition to realistic turbulence observed in lower accuracy predictions for zone F

We recently completed significant refactoring of LAVA for parallel efficiency and demonstrated speedups of 2.4x for comparable cases

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  - Timothy Sandstrom
- LAVA Team:
  - for providing insights and lessons learned from other projects

Video shows density on the cut plane and the vehicle surface in the frame of the vehicle. Red is low, blue is high. Ground is white. *Credit: Timothy Sandstrom*

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